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MAINTENANCE ENTERPRISE RESOURCE PLANNING: INFORMATION VALUE AMONG SUPPLY CHAIN ELEMENTS

by

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This research proposes a new model based on information processing theories to connect the lateral elements of the supply chain, increase vertical information integration, and transform the maintenance supply chain into an efficient system to decrease shortages and excesses of inventory thereby reducing costs. This research will incorporate a simulation to compare the proposed new model with the traditional inventory models. This study claims that, when using the new model in different situations, inventory performance is better than in the traditional models of inventory control. The importance of the results for the maintenance organizations relates to potential improvements in cost and in inventory control while fulfilling mission requirements.

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MAINTENANCE ENTERPRISE RESOURCE PLANNING: INFORMATION VALUE AMONG SUPPLY CHAIN ELEMENTS

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LIST OF ACRONYMS AND ABBREVIATIONS

AD	Actual demand
B2B	Business to business
BAF	Brazilian air force
BOM	Bill of material
CM	Corrective maintenance
CMMS	Computerized maintenance management system
COD	Corrective order demand
CRP	Capacity requirement planning
CWO	Corrective work order
EI	Ending inventory
EO	Ending order
EOQ	Economic order quantity
ER	Ending requisition
ERP	Enterprise resource planning
GST	General systems theory
IOQ	Incremental order quantity
LFL	Lot-for-lot
LHA	Last high assembled
LPC	Last period cost or silver-meal heuristic
LTC	Least total cost
LUC	Least unit cost
MCD	Marginal cost difference
MCT	Maintenance corrective time
MF	Maintenance forecast
MMPS	Maintenance master planning schedule
MMRP	Maintenance material requirement planning
MOP	Maintenance and operation planning
MPS	Master production schedule
MRP	Material requirement planning
MRP-II	Manufacturer resource planning

MTBUR	Mean time between unscheduled replacements
MTBMu	Mean time between maintenance unscheduled
MTTR	Mean time to repair
NHA	Next high assembled
PM	Preventive maintenance
PMS	Purchase management system
POD	Preventive order demand
POQ	Periodic order quantities
PP	Part period balancing
PR	Purchasing requisition
PWO	Preventive work order
QMC	Quantities of material to corrective maintenance
QMP	Quantities of material to preventive maintenance
QPA	Quantity per assembly
RCCP	Rough cut capacity planning
RO	Receiving order
RR	Receiving requisition
SCM	Supply chain management
SI	Starting inventory
SKU	Stock keeping unit
TBO	Time between overhaul
TMS	Transportation management system
TOD	Total demand
VDT	Virtual design team
WIP	Work in process
WMS	Warehouse management system
WO	Work order
WW	Wagner and Whitin model

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I. INTRODUCTION

Supply Chain Management (SCM) seeks to “integrate supply and demand management within and across companies” (Council of Supply Chain Management Porfessionals [CSCMP], 2004). There are two kinds of supply chains: manufacturing and nonmanufacturing. A manufacturing supply chain has the characteristic of producing or transforming products. A nonmanufacturing supply chain is difficult to visualize, though it can come in several forms: military supply chain, environment supply chain, and service supply chain (Ballou & Srivastava, 2007). Service supply chains have the characteristic of maintaining the availability of the products (Cohen, Agrawal, & Agrawal, 2006). A subset of the service supply chain is the maintenance supply chain. The maintenance supply chain involves the maintenance, repair, and overhaul (MRO) organizations and the relationships within and across suppliers and customers. The importance of the maintenance supply chain has increased significantly; industries such as automobiles, white goods, and others have sold so many units that service supply chains have become four or five times larger than their original equipment businesses (Cohen et al., 2006, p. 129).

The 2007 United States Census showed that expenses in repair and maintenance service were US$ 137 billion. In comparison, Aircraft Manufacturing sales were US$ 84 billion (Census Bureau, 2007). Fabry and Schmitz-Urban (2010) wrote that “the maintenance sector in Germany had greater turnover (€ 250 billion) than many other industrial sectors, such as Vehicle Manufacturing” (€ 135 billion). “American businesses and consumers spend approximately US$ 1 trillion every year on assets they already own,” a good part of this on maintenance expenses (Cohen et al., 2006, p. 130).

When Pan Am and Eastern Airlines went bankrupt, they held an excess inventory of spare parts of approximately $700 million and $200 million, respectively (Ghobbar & Friend, 1996). In the military environment, a 2009 U.S. Department of Defense (DOD) report stated that nearly 17 percent of all items in the inventory were inactive and were valued at approximately US$ 15 billion. Most of these items had been purchased as

spares for maintenance purposes, a problem that illustrates the challenge of managing the maintenance supply chain.

The maintenance environment includes components with stochastic failure rates, different types of failures to be repaired, greater numbers of spare parts for repair, and long lead-times to perform maintenance and to purchase spare parts. Frequently, maintenance does not incorporate fluctuations in equipment usage, changes in environmental conditions, and equipment age (Jones, 2006, p. 18.1). When maintenance supply chain elements are disconnected from each other, it causes shortages and excesses of materials. All these factors can result in delays and increased uncertainty in the maintenance process. High levels of uncertainty and a lack of information integration cause excesses and shortages of spare parts. This misinformation causes low availability of aircraft, equipment, or systems, thus increasing holding and shortage costs.

This study applies an information-processing theoretical approach to analyze the information integration among the elements in the maintenance supply chain. It expands on the idea that, with the new technology and techniques (e.g., Enterprise Resource Planning), if the new model connects the elements of the supply chain, it can increase the capacity of information processing, and consequently can decrease uncertainty, response time, and costs.

A. THEORETICAL PERSPECTIVE

This research incorporates elements of systems thinking and information-processing theories, as well as enterprise resource planning techniques. The following discussion provides a brief overview of the theoretical approaches on which this dissertation is based with the related literature.

1. Systems Thinking Theory

In a theoretical perspective for studying the information flow of elements of the supply chain, systems thinking theory provides a useful view to understand integration between elements of a supply chain. Systems theory, with its concepts about feedback loops, self-organization, and collaboration, fits well with the explanation of the elements

of supply chain relationships in that all elements are connected, and if all the elements work together, the whole is greater than the sum of the parts (Capra, 1996).

This research connects the information of the elements of the maintenance supply chain and studies the effects on inventory cost in comparison with a traditional model of inventory control. The experiment will analyze the components of the system working in isolation and in integration with one another. Applying the elements of systems thinking theory, such as self-organizing feedback loops, we can better understand and explain the causality that exists among the elements.

When the elements of the supply chain are integrated, they work as a unified system and inventory costs and response times are improved. When these elements work in isolation in the supply chain, the system property is broken and performance degrades throughout the whole supply chain.

Many authors try to use systems theories to explain phenomena in the supply chain. Zhao, Zhao, and Hou (2006) explained that general system theory (GST) is a meta-theory that can be used in many contexts. Janvier-James (2012) related the supply chain to GST. The supply chain can be explained as a system that has a boundary that divides a system from its environment. Although a supply chain is a manmade system, it is a complex adaptive system designed to improve competiveness and reduce operating costs (Shaoyan, 2009; Shi, Dong & Ruan, 2009; Zhang, Qin, Yan, & Zhao, 2007). Because of this, there are many types of supply chains that adapt and survive in each environment and situation. This research seeks to explain the use of systems theory in the maintenance environment. The information interaction among the elements of the supply chain can transform the elements in a whole system. When the elements of the supply chain are very closely tied, they will work as a system.

2. Information Processing Theory

In this research, information about each component failure was not available and, therefore, maintenance information could not be integrated with supply subunits. Many times, inventory control has to use historic information to predict the purchasing of material, and the supplier generally does not integrate planning information with client

need. This gap causes a high level of uncertainty in the maintenance supply chain environment. Galbraith (1977) defines uncertainty as "the difference between the amount of information necessary to perform a task and the information already possessed by the company". This research focuses on analyzing this environment with information processing theory.

Galbraith (1974) analyzed the relationship between uncertainty and information, and formulated the information processing theory. His theory claims that "the greater the task uncertainty, the greater the amount of information that must be processed among decision makers during task execution in order to achieve a given level of performance." He argues that there are two strategies to ameliorate the uncertainty: 1) reduce the need for information processing and 2) increase the capacity to process information.

Two approaches will be used to analyze the Galbraith theory in this research. The first is to reduce the need for information processing. This approach uses the most common model for inventory control: the economic order quantity with reorder point (EOQ/ROP) model. The second approach is to increase the capacity to process information; this method uses a new model called the maintenance enterprise resource planning (MERP), which connects the information in the supply chain.

Information processing theory is used to explain the relation among the organizations in the supply chain. There are studies that propose structural modification in organizations with vertical analysis and horizontal information systems to increase information processing (Bolon, 1998). Swanson (2003) applied the information-processing model to analyze maintenance management. She found that maintenance organizations respond to the complexity of the environment with the use of computerized maintenance management systems, preventive and predictive maintenance systems, coordination and increased workforce size. Flynn and Flynn (1999, p. 1044) determined that firms found alternatives to processing information where they used "management-intensive solutions, rather than technology-intensive solutions." Levitt's experiments extend information processing theory to a micro-contingency model of organizational behavior (Levitt, Thomsen, Christiansen, Kunz, & Al, 1999; Thomsen, Levitt, & Nass, 2005). There is no study of integration among the elements of the supply chain that

shows the implication of connecting lateral and vertical information to decrease uncertainty. This research addresses that gap to extend the use of information processing theory to supply chain elements.

3. Enterprise Resource Planning

Vollmann, Berry, Whybark, and Jacobs(2005) present two interesting definitions of ERP. For the information technology community, "ERP is a term that integrates the application program in finance, manufacturing, logistics, sales and marketing, human resources, and the other functions in an organization." From the manager's view, "ERP represents a comprehensive software approach to support decisions current with planning and controlling the business firm" (Vollmann et al., 2005, p. 109). In other words, ERP is a term so comprehensive that it supports both the supply chain and information science areas. ERP seeks to integrate information of the organization through best-practice functionality and systems interoperability with common databases and interfaces (Markus, Axline, Petrie, & Tanis, 2000).

ERP started with the concept of material requirement planning (MRP). MRP's function is to prepare a master production schedule (MPS) and a list of material that the company has to purchase. This technique got started in 1960 and became more popular with the development of computers. Later, this technique evolved to manufacturing resource planning (MRP II) that expanded to the enterprise level; more computer technology was used, more integrated functioning was undertaken, and decision-making was incorporated. ERP was an extension of MRP II that sought to integrate information and processes across companies using the Internet. This research uses MRP to build a model that connects the elements of the maintenance supply chain to decrease uncertainty.

In the area of ERP, some researchers present solutions to mitigate the problem. Ghobbar and Friend (1996) studied aircraft companies and showed that at least 50 percent of companies were not satisfied with their system of inventory control. Newman (1985) proposed an MRP model where "M = preventative maintenance." He argued that MRP could be used for preventative maintenance requirement planning (Newman, 1985).

Molinder (1997) used “simulation with the objective of analyzing the effects of different sources of uncertainty in MRP systems” (Molinder, 1997). Ettkin and Jahnig (1986) presented a framework for adaptation of MRP II to maintenance functions for waste reduction. They argued that this model can be used successfully in maintenance management because of similarities between manufacturing and maintenance processes (Ettkin & Jahnig, 1986). However, none of these researchers presented a model that integrated all the elements of the maintenance supply chain. “Companies that apply ERP software without customizing the need of this environment have bad experience and deliver poor service” (Cohen et al., 2006). This dissertation seeks to fill this gap by testing a new integration model between maintenance supply chain elements that match inventory to maintenance requirements to decrease inventory costs. Now it is necessary to define this environment to understand the problem.

B. CONTEXT

This research discusses information integration in the supply chain, more specifically, the maintenance supply chain. The following provides a brief overview of these concepts to situate the reader in the research context.

1. Information Sciences and Supply Chain

SCM “integrates supply and demand managements within and across companies” (CSCMP, 2004). This new approach tries to explain the relations within companies and across companies. Information sciences, as the name indicates, is the study of information and its interrelations; if information is a flow and everything is connected, then everything passes some messages. Information sciences can be defined as a science that studies the relation of information within and across disciplines.

Supply chain science studies the network of processes and stock points used to deliver goods and services to customers (Hopp, 2011). Information sciences has a subset that claims to understand the process of developing and using information and communication technologies in organizations (Avgerou, 2000). Thus, supply chain science works with process itself, and information science focuses on the communication of information within the processes. One science can complement the other.

This concept is very useful because if a supply chain generally has high information variability, uncertainty, and poor visualization of information, then information sciences can help to clarify how to connect the elements for efficient communication and integration.

2. Maintenance Supply Chain

A subset in the supply chain is the maintenance supply chain that involves the maintenance, repair, and overhaul organizations and the relationship within and across suppliers and customers; MRO organizations specialize in actions necessary to restore or retain an item in an effective operating state (Blanchard, Verma, & Peterson, 1995, p. 1).

To manage the maintenance supply chain, managers have to work with client information about the equipment as well as failures, operations, and utilization forecasts. Many times, they cannot forecast when the failures will happen. When failures happen, maintenance shops do not know the material that they will use to fix the failure. Many times, the material that is used in maintenance is not connected to production, so uncertainty is present in many processes.

For the manufacturer supply chain, the demand is also challenging, but they know the material needed to assemble a system and the material supplier. In this case, the supplier's lead time can vary. By contrast, the maintenance supply chain has a lot of variability because many items are discontinued and difficult to purchase.

Although there are similarities among manufacturing industries, such as the traditional manufacturing process (e.g., shop-floor scheduling and assembly) (Gaudette, 2003), both types of supply chains involve suppliers, plants, and customers. There is, however, a significant difference between the characteristics of the maintenance supply chain and the manufacturer supply chain that there is need to develop a specific framework for the maintenance environment.

To illustrate this environment, this research will use the example of a military aircraft system. The research could use other examples (e.g., car, TV, computer environment), but the aircraft system is best because it has all the elements needed to

describe the maintenance environment. This researcher describes the maintenance supply chain of the aircraft in terms of the maintenance and supply structure, and analyzes the interaction of elements of this supply chain.

3. Maintenance Environment

This section offers a brief overview of the aircraft maintenance process. It is important to understand this issue because the research uses aircraft maintenance as the object of experiment.

a. Maintenance and Supply Structure

Military aircraft maintenance structure can have three levels of maintenance and supply. Individual flight squadrons are responsible for the organizational maintenance level (e.g., repetitive maintenance such as lubrication), while the respective airbase shop provides the intermediate level of maintenance (e.g., preventive and corrective maintenance). The highest type of maintenance is done by a maintenance shop depot or supplier/manufacturer maintenance organization; this level performs more complex maintenance (e.g., major repair, overhaul). Figure 1 presents the maintenance flow.

In the supply structure, flight squadrons have material stockpiled to use in organizational maintenance. The airbase depot supplies material to the first and second level of maintenance. The supply depot supplies material to the intermediate level. To replace material at the depot level, inventory planners manage and request all supplies from the depot level (e.g., national inventory control points, NICPs).

Other systems can have the same structure as the one just described, or they can be different depending on the specifics. For example, the TV system supply chain generally has only the intermediate level and rarely has the third level of maintenance. In the auto industry, there are three levels of maintenance. These levels are organizational (e.g., owners change oil, tires), intermediate (e.g., dealers do preventive maintenance or corrective maintenance), and manufacturer/depot (e.g., some equipment to repair). Therefore, the design of the supply and maintenance sectors can vary according to the system.

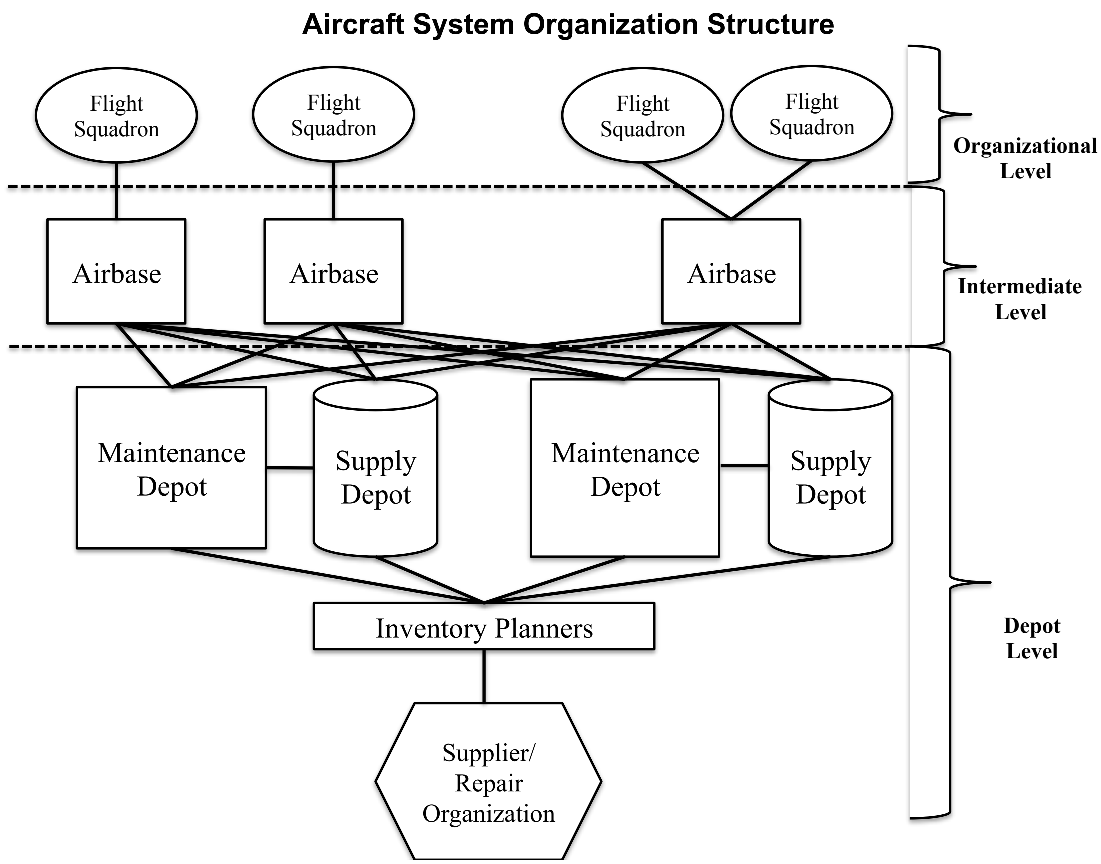

Figure 1. Example of maintenance and supply structure.

b. System Configuration Management

System configuration management is very important to understand the system structure. A system is assembled according to the type of item: repairable items (doing maintenance), nonrepairable items (no maintenance, replace), and consumption items (used in the maintenance, spare parts). A system can have many subsystems within its respective components. Each component has specific characteristics of maintenance and operation.

In the example in Figure 2, an aircraft is called "last high item assembled" (LHA). The aircraft has a specific program of preventive and corrective maintenance, which is separate from the program for each of its components.

The aircraft has many systems, such as the hydraulics, communications, or the engine. These systems have components that are assembled in the aircraft. Each item is

designated by the relative order in which the items must be assembled. In the case of the example, the aircraft is next high assembled (NHA) for the engine; for the fuel filter, the NHA is the engine. The components can be repairable, nonrepairable, or consumption items. In the illustrated example, the aircraft has two radios that belong to the communication system. These items are “on condition,” which means that maintenance is done only when the item fails. This maintenance is done at the depot level. The mean time between unscheduled removal MTBUR is 1,000 hours flown.

The engine is monitored by hours flown and time. The time between overhaul is 3,000 hours or five years; when the engine reaches the number of hours flown or time of use, it goes to the maintenance depot for overhaul maintenance. The MTBUR is 4,000 hours. The engine has components (e.g., fuel filter, fuel pump) that are monitored separately.

The number of repairable components can vary from tens to hundreds, depending on the type of aircraft. Figure 2 presents a basic system configuration of the respective position and maintenance of each component of an aircraft. The real configuration of the aircraft is represented when the serial number of each component is registered in the software or logbook of the aircraft. When this happens, the components start to be monitored. To achieve the goals of reliability and availability, each piece of equipment is designed with its own maintenance plan.

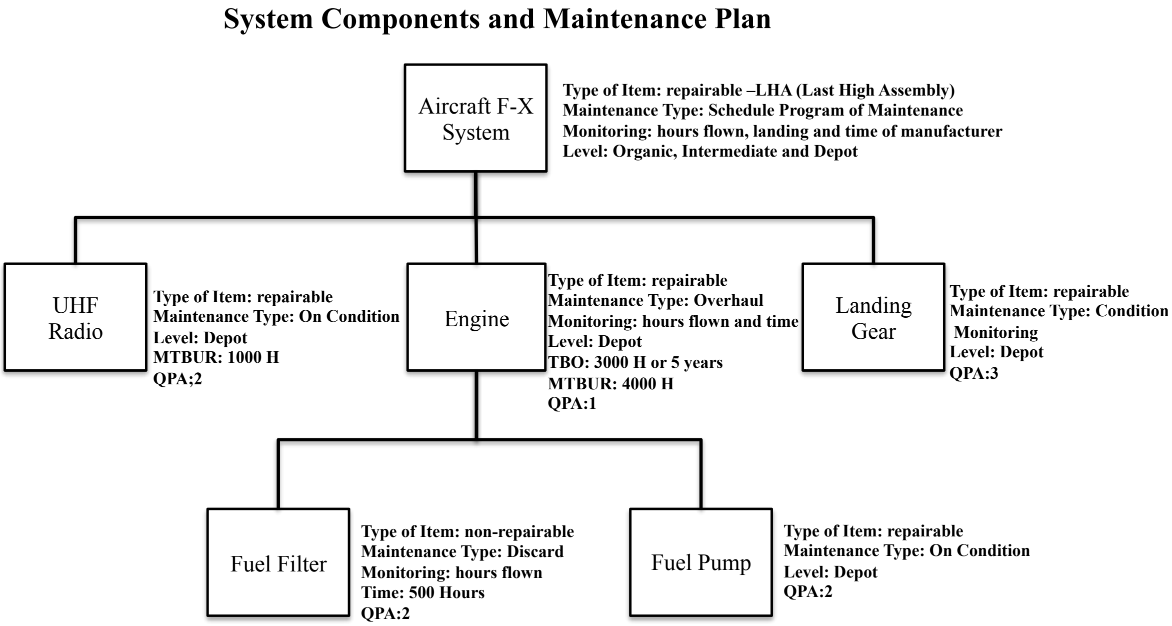

Figure 2. Example of system configuration.

c. *Aircraft Maintenance Management*

In this example, the hypothetical F-X aircraft has a scheduled program of maintenance that can be done in many levels. Table 1 shows an example of the inspection planning. Each maintenance level contains a set of tasks (e.g., inspection, replacement, calibration) that contains the necessary material, personnel hours/specializations, manual reference, and support equipment.

Table 1. Inspection planning.

Level	Periodic hours/flown	Maintenance code
Organic	100	A
Intermediate	500	B
Depot	2,000	C
Retired	20,000	

The chronologic maintenance cycle of aircraft is presented in Table 2. The aircraft has a sequence of maintenance until it reaches the depot level. After depot maintenance is done, the aircraft starts a new cycle until the equipment retires.

Table 2. Example of maintenance cycle.

Maintenance code	**Number of hours flown**	**Maintenance code**	**Number of hours flown**
A	100	A	1,100
A	200	A	1,200
A	300	A	1,300
A	400	A	1,400
B	500	B	1,500
A	600	A	1,600
A	700	A	1,700
A	800	A	1,800
A	900	A	1,900
B	1,000	C	2,000

d. Repairable Maintenance Management

When a component is repairable, it can be in a condition monitoring, on condition, or overhaul. For the items that are on condition, the mechanics do tasks to monitor the condition of the item; if there are some problems, the item is removed and sent to the appropriate level of maintenance. Generally, these levels execute corrective maintenance.

If the items are in the condition monitoring, the mechanic monitors surveillance of the equipment or system to ensure proper operation. When it is deemed to be operating properly, the item is removed and follows the same process of an on-condition item.

When an item is monitored by overhaul, it is monitored until the limit of the overhaul time. In this time, the item has to be removed and sent to maintenance. Overhaul contains a set of tasks (e.g., inspection, replace, calibration) that covers the need of material, personnel hours/specializations, manual reference, and support equipment.

For a nonrepairable and monitored item, when it meets its time limit, the item is replaced. For any kind of repairable item, if it fails, the item is sent to the appropriate level of maintenance for corrective maintenance.

e. Inventory Management

Inventory management controls the level of stock of each component. When the stock reaches the reorder point, a requisition is done, and the superior level attends to the material. When the depot level reaches the reorder point, the inventory planners send a requisition to suppliers. The reorder point and order quantity are calculated using historical data.

C. PROBLEM STATEMENT

Generally, maintenance is performance only when it is requested (Heizer & Render, 2007). Inventory controls are managed according to historical consumption. There is no connection between the maintenance requirement and inventory need. This is a characteristic of a push system based on the historical data. If operators use more equipment than they did in the past, inventory control cannot predict the need for material.

The system life cycle clearly shows that each phase is dependent on the other. When the engineers conceptualize a system (e.g., car, aircraft, TV), there are forecasts of consumable material based on maintenance requirements. When the system is fielded, the connection between maintenance and supply is broken apart and each function works separately. When the elements of the system are disconnected, its system properties are broken apart as well, and the system cannot work as a whole (Jones, 2006).

What is observed is that supply works following the planning process without connection to the other elements of the supply chain; and there is a disconnection among the elements that causes the maintenance and material consumption. Maintenance and inventory planning does not take into account variations in the use of equipment, atypical situations of increasing failure rates, or even changes in the mode of use of the equipment. All these factors may add to the uncertainty of the planning process.

The problem then is that the high level of uncertainty and the lack of integration of information cause inventory mismatch (excesses and shortages of spare parts). It is a serious problem because it affects availability of aircraft/equipment/systems and increases inventory costs.

D. RESEARCH QUESTION

The purpose of this experiment is to test a new information integration model for maintenance supply chain elements to match inventory with maintenance requirements. This study compares the new model with traditional inventory control models to analyze the inventory costs and response time. This research is important because the result tries to reduce uncertainty and, consequently, to decrease cost and increase the availability of the equipment.

This study applies systems thinking theory and an information processing theoretical approach to analyzing information integration among the elements in the maintenance supply chain. It expands on the idea that with new technology and techniques (e.g., ERP), if the new model connects the elements of a supply chain, it can increase the capacity for information processing and, consequently, decreases uncertainty and costs. This new model is called maintenance enterprise resource planning (MERP).

The specific research question addressed in this dissertation is: Does integrating information in the maintenance supply chain affect uncertainty and consequently, inventory performance?

E. RESEARCH APPROACH

This dissertation uses the quantitative method to compare two models in a maintenance environment in terms of cost and response time in different situations. The scenario comparison uses full-factorial simulation that consists of four experiments.

The first experiment seeks to simulate and validate each model using regression analysis. After the models are validated, the second experiment seeks to compare the inventory costs by using a dependent t-test to compare the means. This empirical

experiment controls all internal variables and seeks to study the relations "under pure and uncontaminated conditions" (Kerlinger & Lee, 1999, p. 581).

In the third experiment, some independent variables will be fixed, and real data from maintenance operations of the Brazilian Air Force will be used to compare the inventory costs. In the last experiment, an independent variable will be fixed, and abrupt variation of this independent variable will be simulated to observe the response time of the models. The goal of the experiments is to increase the efficient of inventory control.

The research will test the following hypotheses:

First Experiment—Simulation Models Validation

H_1 : The EOQ/ROP and MERP model predict significantly well the inventory costs.

H_2 : β contributions affect the inventory costs

Second Experiment—Comparing Model Costs

H_3 : MERP lowers inventory costs compared to EOQ/ROP. $IC_{MERP} < IC_{EOQ/ROP}$

Third Experiment—Comparing Model Costs with Real Data

H_4 : MERP lowers inventory costs compared to EOQ/ROP. $IC_{MERP} < IC_{EOQ/ROP}$

Fourth Experiment—Response Time Experiment

H_5 : MERP lowers inventory costs compared to EOQ/ROP. $IC_{MERP} < IC_{EOQ/ROP}$

F. THEORETICAL CONTRIBUTION PROPOSAL

Corley and Gioia (2011) argue that a theoretical contribution is a function of originality and utility. The originality view is based on the potential contribution of the articulated new insights. They divided this function into two types: incremental insights and revelatory insight (Corley & Gioia, 2011, pp. 12–17). The utility function can be seen as the potential to improve current research practice or the current managerial practice. They divided this function into two categories: scientific and practical utility (Corley & Gioia, 2011, pp. 17–18).

This research seeks to extend the use of information processing theory to supply chain management by creating a model that integrates information within and across the supply chain. Because of the complexity of the maintenance environment, the model

organizes and integrates information among the elements of the supply chain (e.g., supplier, organization, users). The MERP framework increases the integration capability and, consequently, can increase supply chain performance.

This research adds a new scientific approach to MRP by adding a new theory on the use of MRP. In the early days, “MRP was neglected in academic curricula in favor of intellectually challenging statistical and mathematical techniques. Academics considered the study of MRP vocational rather than scientific” (Ptak & Smith, 2011, p. 375).

Further, this model seeks to build a new framework in the maintenance supply chain. A literature review shows scarce research about models that attend to this environment. This model brings a new management dimension to the maintenance supply chain.

G. ORGANIZATION OF WORK

Chapter II provides a literature review to analyze the theoretical foundations and techniques that support this research, including systems thinking, information processing theory, supply chain science, maintainability, enterprise resource planning techniques, and related studies in this area. In Chapter III, the elements of the new model will be demonstrated and explained. In Chapter IV, the research design is exhibited. In Chapter V, the data is analyzed and explained. Chapter VI completes this dissertation with a summary of the results, theoretical contributions, and limitations, and suggests future research.

II. LITERATURE REVIEW

The literature review is divided into five sections. The researcher seeks to situate the reader in the most recent critical view of the studied area. To understand the research aspect, the literature review begins by explaining the supply chain and types of supply chains in the maintenance area. Following this foundation, the researcher explains the main aspects of maintenance and the challenge in this environment. Having explained the challenge, the research considers possible techniques that can address this problem, particularly, enterprise resource planning (ERP/MRP), the most recent updates to this model, and its possible use in the maintenance environment. Then, the research presents the two theories that support this dissertation with the latest studies and their application to the problem, showing the gaps and hypotheses to be tested.

A. SUPPLY CHAIN MANAGEMENT AND ITS ROUTE TO "NORMAL SCIENCE"

What is supply chain management science? Is it indeed a science? How has it come to be so? What path has it followed? To understand the status of supply chain management as a science, first one must trace its progress to what is more popularly known as supply chain management. The phrase supply chain management was first used in 1982 (Blanchard, 2010, p. 58). Thirty years later, one can trace the evolution of a great conceptual transformation concerning the relations and the flow of information, goods, and payments between suppliers, producers, and consumers. SCM has arisen very quickly, during which time many existing professional societies and journals have made it their focus, while new societies and journals dedicated to SCM were created. New disciplines have been introduced in schools, where SCM is now taught at all levels. How, in less than three decades, could such a new concept coalesce so quickly? This section applies a Kuhnian analysis to understand SCM and its evolution.

1. Elements of Kuhn's Theory

Kuhn states, "history suggests that the road to a firm research consensus is extraordinarily arduous" (1970). When this consensus occurs, however, "normal science"

is established. In this context, normal science is defined as “research firmly based upon one or more past scientific achievements, achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice” (Kuhn, 1970). Normal science primarily involves matters of puzzle solving (Okasha, 2002), but for Kuhn, a puzzle is different from a problem; a puzzle has not been solved yet—but it does have a solution. A problem might not have a solution (Godfrey-Smith, 2003, p. 81).

Kuhn (1970) argues that science develops through the addition of a new thrust to the stock of an old thrust. A mature science undergoes alternating normal and revolutionary phases. Normal science has key theories and values that help to solve many puzzles and a disciplinary matrix to accumulate knowledge. Often, a new truth does not fit the old paradigm. When this truth is scarce, it can be ignored; when it increases, a crisis starts in the scientific community, and the disciplinary matrix undergoes revision (Bird, 2012). Okasha (2002) explains that a paradigm is an “entire scientific outlook—a constellation of shared assumptions, beliefs and values that unite a scientific community and allow normal science to take place.”

The transformation to normal science is not an easy one; development does not happen quickly. Transformation takes a long time, beginning with many small but interconnected findings (Kuhn, 1970). Kuhn argues that a succession of many paradigm transformations creates a scientific revolution. A transformation can start a long time before new paradigms are conceived. During these times, scientists contribute what he calls a “paradigmatic observation.” Special clusters are formed that explain particular facts of a phenomenon, but they remain as outstanding problems for further research (Kuhn, 1970, p. 12). According to Bird (2012), “Kuhn describes an immature science, in what he sometimes calls its ‘pre-paradigm’ period, as lacking consensus. Competing schools of thought possess differing procedures, theories, even metaphysical presuppositions. Consequently there is little opportunity for collective progress.”

During a pre-paradigm period, facts and observations begin to arise. When the observations can no longer be reconciled with the old paradigm, these observations transform into anomalies. These are puzzles that have resisted a solution. When

anomalies arise, new paradigms may appear to explain the phenomenon. The surge of new paradigms marks the beginning of a period of revolutionary science (Okasha, 2002, p. 82).

A new paradigm brings puzzle solutions that may not solve all problems, but the puzzle solution may suggest other puzzles of the same kind that can offer new opportunities to research using the same approach that the puzzle solution used. This time, after competition between paradigms subsides, a paradigm consensus develops as a group or an individual produces syntheses that attract more students of that knowledge domain (Kuhn, 1970).

When normal science begins, students of that knowledge domain convert to a new paradigm and new schools appear. The research community develops specialized equipment and techniques to investigate specific questions. Rigid definitions are created and the group begins a new discipline and profession. With the rise of knowledge, there are "formations of specialized journals and foundations of specialists' societies" (Kuhn, 1970).

With the definition consolidated, scientists initiate in-depth research and record their findings in books. The normal science is consolidated until new paradigms appear and the cycle starts again. Many authors use Kuhn's path to explain the evolution of sciences. Gary Gutting's bibliography lists 119 works about Thomas Kuhn in a variety of sciences (Cushing, 1989).

2. Supply Chain Management—The Route to Normal Science

This section is divided into the pre-paradigm period, the revolutionary science period, and the route to normal science following Kuhn's analysis, as it applies to SCM.

a. Pre-paradigm Period

The first paradigm that history reveals is the term "logistics." Although the term had not yet been coined with a real definition, "logistical" concepts were used in many military campaigns with no consolidation of a real concept. Those military campaigns employed notions of logistics that invariably involved the movement of physical goods

from one location to another. The route to revolutionary science begins with paradigmatic observations and is characterized by several incompatible and incomplete concepts and theories.

The first reported use of the term "logistics" was seen during the time of Alexander the Great (356–323 BC). He focused on sufficient logistical support for his army to conquer the many territories that he attacked (Engels, 1980). The Roman Empire (264 BC–235 AD) adopted some of Alexander's logistical tactics, but further developed their own. The advent of the term "logistics" can be traced to the Romans' wars, when military officers known as "logistikas" were responsible for supplying and managing the resources of the different Roman legions (Roth, 2012). Another example of logistics used in the past was Genghis Khan's campaign (1162–1227 AD). Specialized troops of craftsmen were skilled in building complex siege machines from local materials, eliminating the need to transport them over long distances to the siege location. They perfected the sapping of walls, rendering static defenses ineffective (Weatherford, 2004).

The Napoleonic Age generated a concept of logistics that the French "defined as the art of moving troops." This French term "logistique" is found in *The Oxford Dictionary* published in 1898. An entry written by William Lewer defined logistics as "the art of moving and quartering troops, i.e., quartermaster-general's work" ("Logistics n2," 2012; Lummus, Krumwiede, & Vokurka, 2001). *The Dictionary of Modern War* describes logistics as "all activities and methods connected with the supply of armed force organizations, including storage requirements, transport and distribution" (Luttwak, 1971).

From 330 BC to 1900 AD, the evolution of the concept progressed quite slowly. Kuhn discusses this same phenomenon, referring to electricity theory when he writes that the "first four decades of the 18th century possessed far more information about electrical phenomena than had their 16th century predecessors" (Kuhn, 1970). Perhaps we can say that the twentieth century was the age of supply chain evolution.

With World Wars I and II, logistics was critical to support great movements of troops and supplies. Military schools intensified the use of the term, and it came to

represent manifold functions including procurement, maintenance, and transportation of military facilities, materiel, and personnel (Ballou, 2007).

b. Revolutionary Science Period

In the twentieth century, the term logistics finally was defined, but many anomalies arose related to the term. The term logistics could not explain all concepts and theories that were developed. Logistics as a concept remained very fragmented. Ballou (2007, p. 376) says that a reason for this is a lack of understanding of key cost tradeoffs, the inertia of traditions and conventions, and the evolutionary state of organizations at the time. From the 1950s to the 1970s, companies did not seem to realize that each functional activity depended on the others. That is when two principal activities developed separately: materials management and physical distribution.

Subsequently, many theories and techniques seemed to integrate other functional terms that are used by industry, such as material requirement planning (1964), reverse logistics (1971), customer/supplier relationship (1969), just-in-time (circa 1970–1982), theory of constraint (1984), and electronic data interchange (EDI, 1975–1985), confirming Kuhn's observation that "prior to the 'revolution' there were many small areas of research founded on different assumptions or attempting to explain different phenomena" (Kuhn, 1970).

By the end of the 1970s, many terms were available, such as distribution, logistics, material management, and value chains, but they were not integrated. As Ballou (2007) explains, production and purchasing were studied separately. The anomalies accumulated to the point where it became difficult for logistics to cover all new concepts. Kuhn refers to this as a crisis. The community needed to consolidate its body of knowledge. In 1985, the National Council of Physical Distribution Management was renamed the Council of Logistics Management (CLM), offering this definition:

> Logistics Management plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements. (Council of Logistics Management, 1998, quoted in Lummus et al., 2001, p. 426)

This definition sought to integrate the domains of materiel management and physical distribution. Its key attributes are integrated management, process orientation, and a focus on customer requirements.

Despite the advent of a logistics management definition, this term did not embrace all concepts. Logistics is so connected with transportation and distribution that it was difficult to incorporate the relationship among suppliers, producers, and customers, in addition to materiel management. In 1982, British logistician and consultant Keith Oliver

> began to develop a vision for tearing down the functional silos that separated production, marketing, distribution, sales, and finance, to generate a step-function reduction in inventory, and a simultaneous improvement in customer service. Looking for a catchy phrase to describe the concept, the consulting team proposed the term 'integrated inventory management.' (Laseter & Oliver, 2003)

In a public interview with the *Financial Times* on June 4, 1982, Oliver was the first to use the term "supply chain management" (Blanchard, 2010). After Oliver's first use of the term, an intense debate arose between "logistics" and "supply chain" and the definition was revised many times. It caused Ballou (2007, p. 379) to ask exactly what SCM was, when compared with logistics and physical distribution.

In 2004, the Council of Logistics Management was renamed again to the Council of Supply Chain Management Professionals (CSCMP). The CSCMP redefined supply chain management as encompassing:

> …the planning and management of all activities involved in sourcing and procurement, conversion, and all Logistics Management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and customers. In essence, Supply Chain Management integrates supply and demand management within and across companies. (CSCMP, 2004)

This new definition integrated products, information, and cash flow management throughout all channels. In Figure 3, Ballou (2007) illustrates this evolution.

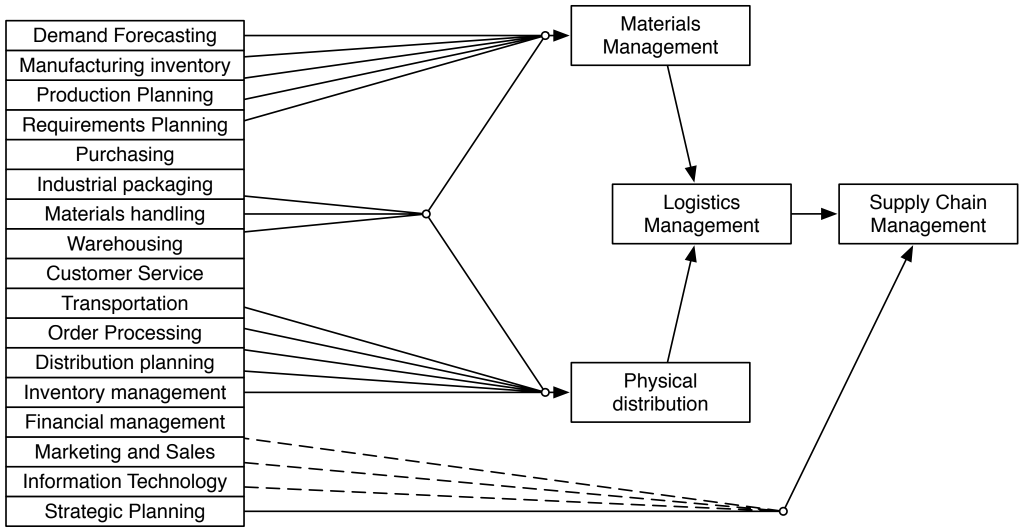

Figure 3. The evolution of supply chain management (after Ballou, 2007).

One can see that supply chain management integrates the management of product flow processes across functions and between channel members. Secondly, logistics is regarded as a subset of SCM. Finally, purchasing and production are within the scope of SCM. Many areas of a firm embrace SCM (Ballou, 2007). "Collaboration among supply chain members is at the heart of SCM and will be the key to its future success" (Ballou, 2007, p. 344). A new paradigm arises and revolutionary science happens. At that point, SCM is on its way to becoming normal science.

3. Normal Science Period of SCM—Science, Theory, and Definition

Kuhn affirms that the consolidation of a new paradigm can require as much as one or two generations of scientists (Kuhn, 1970). He suggests that revolutionary science would be sufficiently open-ended to enable others to develop theories from new paradigms. The debates about logistics and supply chains continue, but now the concepts of SCM have been consolidated. "Indeed, by today's standards, the original scope of supply chain management appears quite narrow" (Laseter & Oliver, 2003). The path to normal science was not easy, however, because the term SCM is quite new. Kuhn suggests that the path to normal science passes through rigid definition, the creation of a discipline, a journal, and a textbook.

The first step to normal science is the definition. Kuhn writes that a group produces a synthesis and, with this definition, other members converge to a new paradigm. At that time, the new group would establish a rigid definition (Kuhn, p. 19). Philosophers have tried to prove a distinction between scientific knowledge and its look-alikes. This distinction, called the demarcation problem, is "part of the larger task to determine which beliefs are epistemically warranted" (Hansson, 2012).

An accurate definition of science is that it embraces a wide range of diverse disciplines and theories (Okasha, 2002) and seeks "to build and organize knowledge in the form of testable explanations and predictions about the universe" (Heilbron, 2003). Science is a contingent form of human understanding of the world. We can deduce that science builds and organizes knowledge with its explanations and predictions. Fraassen adds that the ultimate importance of science is explanation. Explanation is an application of science (Schick, 1999, p. 88).

Supply chain management science embraces the production, inventory, transportation, and other functions, relations with customers and suppliers, and the relations among the functions. SCM seeks to predict and explain why and how the phenomena among the elements of the supply chain happen. This new science claims to build and organize the knowledge and relationships that are used among the supply chain elements. Although we have an approved definition of SCM by the CSCMP, many authors still define SCM differently. Table 3 shows some of these definitions:

Table 3. SCM definitions.

Definition of SCM	**Reference**
A set of approaches used to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed in the right quantities, to the right locations, and at the right time, in order to minimize system-wide cost while satisfying level requirements.	(Simchi-Levi, Kaminsky, & Simchi-Levi, 2007)
The integration of the activities that procure materials and services, transform them into intermediate goods and final products, and deliver them to customers.	(Heizer & Render, 2007)
SCM consists of all stages involved, directly or indirectly, in fulfilling a customer request.	(Meindl & Chopra, 2003)

Definition of SCM	Reference
The integration of key business processes from end-users through original suppliers that provides products, services, and information that add value for customers and other stakeholders.	(Lambert, 2008)
The management of materials and information across the entire supply chain, from suppliers to component producers to final assemblers to distribution (warehouse and retailers), and ultimately to the consumer.	(Silver, Pyke, & Peterson, 1998)

A review of these definitions demonstrates that SCM integrates the supplier-producer-distributer-customer cycle. In reality, the definitions are so broad because SCM addresses nearly all functions of a company. SCM studies how a supplier can influence a company and a customer, and how a company interacts with its suppliers and customers. SCM appears to study all interactions—inside a company, among suppliers, and with customers.

If science embraces a wide number of theories, we have to define and discuss theory. In history, we can see that many philosophers tried to contribute to defining what a scientific theory is. Why is this short word so dynamic and difficult to explain? This is not an easy task. The National Academy of Sciences defines a scientific theory as "a well-substantiated explanation of some aspect of the natural world, based on a body of facts that have been repeatedly confirmed through observation and experiment" (*Science and Creationism*, 1999, p. 2). Many philosophers claim that theory can be used in a different way. The positivistic view is that theory can be used to explain the interrelations among variables formed into a hypothesis (Creswell, 2009). In contrast, the social-constructivist view uses theory as a broad explanation for behaviors and attitudes or an overall orienting lens for the study of questions of gender, class, and race (Creswell, 2009).

In a supply chain environment, a question remains: what is the theory of supply chain management? Halldorsson, Kotzab, Mikkola, & Skjott-Larsen (2007) explain that "depending on the concrete situation, one can choose one theory as the dominant explanatory theory, and then complement it with one or several of the other theoretical perspectives." Ketchen and Hult (2007) write that organization theory has the potential to offer provocative and helpful wisdom to the field of SCM. As a result, enormous

opportunities exist to integrate insights from organization theory to understand why some supply chains excel while others do not.

In his 2011 book, Hopp (2011, pp. 6–7)) presented an interesting definition of a supply chain:

> a goal-oriented network of processes and stock points used to deliver goods and services to customers. Processes represent the individual activities involved in the maintenance tasks and distribution of goods and services. The stock points represent locations in the supply chain where inventory are held.

Behind Hopp's definition lie two important theories: systems theory and network theory. Supply chain management is at the juncture of many systems that connect though informational and physical networks. If a supply chain is a large system and a network, then SCM follows the principles of these theories.

Kuhn (1970) says that "a paradigm transforms a group previously interested merely in the study of nature into a profession or, at least, a discipline." SCM has enjoyed great success in this area. Courses and classes about supply chain quickly emerged as universities and institutes responded to the increasing demand for this body of knowledge. Journals and a society were created and, nowadays, these institutions study phenomena in SCM.

The last step witnesses the preparation of textbooks, and occurs when the paradigm "can be taken for granted, the scientist needs to build his field anew, starting from principles and justifying the use of each concept introduced" (Kuhn, 1970). In this phase, a paradigm is narrower and many researchers discuss new theories and show solutions for many problems. They have more time to concentrate exclusively on the phenomenon.

The route of SCM to normal science originated thousands of years ago, in the military campaigns of Alexander, the Roman Empire, and Genghis Khan. The term logistics was the first paradigm, created in the Napoleonic Age. In the twentieth century, anomalies arose, and many concepts were created that the old paradigm could not embrace. This was a time of revolutionary science.

At the end of the twentieth century, a new paradigm began and has developed very quickly. A discipline began, professions started, textbooks were created, and supply chain science continues to consolidate as a normal science. Although, in the last 30 years, acceptance of the term has grown rapidly, it appears to require further refinement. Some might consider the debates between "logistics" and "SCM" to be over; for others, SCM concepts may need further solidification. It may be in academia and journals where this consolidation and solidification occurs.

SCM is in constant development, and as a paradigm, it is real. Following Kuhn again, a new paradigm can take more than two generations to gain adherents. SCM as a paradigm has been with us for 30 years. It claims to build and organize the knowledge about why and how the phenomena among the elements of the supply chain occur. It can be argued that it is well along the path of revolutionary science toward normal science, as the next decade may tell. Figure 4. presents this SCM evolution based on Kuhn.

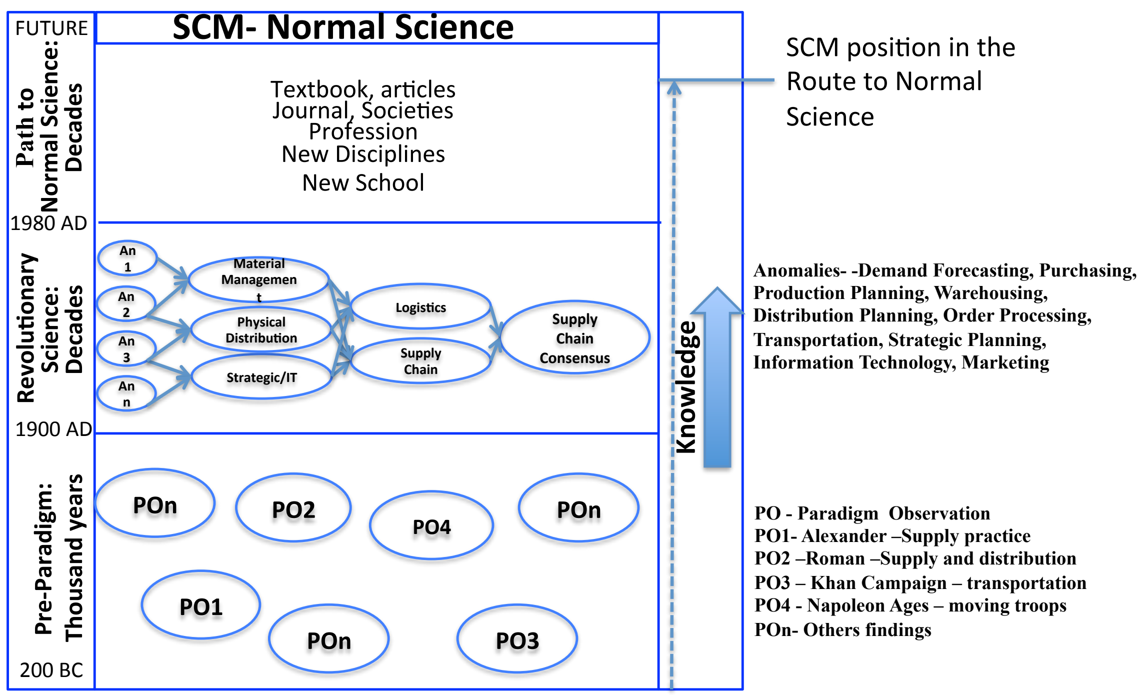

Figure 4. SCM's route to normal science.

4. Challenging Nature of Supply Chain Management

The studies about the supply chain concept are relativity new; the phenomena that drive this environment are challenging to explain because there are so many interactions among the elements of a supply chain that it is difficult to isolate a single process. Predicting and matching the supply and demand in such a complex network thus becomes challenging in supply chain management (Simchi-Levi et al., 2007).

This environment is a dynamic system where the customer pattern is not the only source of uncertainty; other factors such as supplier deliveries, production, and transportation bring new elements to the chain that force the entire chain to adapt (Simchi-Levi et al., 2007). Then, to find explanation and theories in this complex network and dynamic system is a challenge to managers and scientist.

"Matching supply and demand is a major challenge" (Simchi-Levi et al., 2007, p. 5), where diverse types of demand cause different uses of inventory models. If a company has an excess or shortage of material, cost can increase substantially. Risk is a constant; endogenous and exogenous uncertainty increase the operational risk in a supply chain (Groznik & Trkman, 2012). Galbraith (1974) defines uncertainty as the difference between what you know and what we need to know. Knight (2012) explains that risk is uncertainty that can be measured. In other words, in a supply chain environment, the managers have to measure the risk and try to mitigate its influence on the supply chain.

Factors such as inventory and back-order levels across the supply chain, different frameworks to integrate communication among the elements of supply chain, and the many and different information systems to support the supply chain activities greatly increase this risk management (Groznik & Trkman, 2012; Simchi-Levi et al., 2007). It is vital to view the supply chain from the perspective of information, where "information flow is an integral part of SCM and material flow is closely dependent on information flow" (Groznik & Trkman, 2012). Many mechanisms can be used to improve information flow; technologies, such as decision-support systems, electronic data interchanges (EDI), and e-business, can help integrate lateral and vertical information in a supply chain.

Managers cannot eliminate uncertainty, but they can find mechanisms to reduce the risk and make the supply chain more stable. The first mechanism is identifying the type of supply chain and the associated risk. Each type of supply chain works differently, with different risks and solutions. So, what kind of supply chain is there?

5. Types of Supply Chains

Each organization has to identify the right supply chain to meet its needs. One of the most common is the manufacturing supply chain. This supply chain has the characteristic of producing or transforming products. The demand aspect of this supply chain is predictable and can be forecast, the stock keeping unit (SKU) is limited, and the goal is maximizing the velocity of resource in the supply chain (Cohen et al., 2006).

Ballou (2007) describes some different supply chains in nonmanufacturing environments. Supply chains in nonmanufacturing are sometimes difficult to visualize because many times they do not actually function "in terms of moving and storing a physical product" like the manufacturing supply chain (Ballou & Srivastava, 2007, p. 22).

A military supply chain is a good example of nonmanufacturing. Although it shares similarities with a private supply chain, during war, a military supply chain is unique. To plan and execute operations like the Normandy landings or Iraq invasion, the elements and challenges are different and so complex that they make this environment hard to manage (Ballou & Srivastava, 2007, pp. 24–25).

Another example of a nonmanufacturing supply chain is an environmental supply chain. Recycling, packaging materials, transporting hazardous materials, or refurbishing products for resale are some activities of this supply chain. An environmental supply chain creates additional complications because of different governmental regulations in each country and the unique nature of each environmental situation.

The service industry can be another useful nonmanufacturing example. Businesses such as fast-food restaurants, lodging, retail banking, or hospitals encompass activities of service supply chains, even though some of these companies may be distributing an intangible, nonphysical product (Ballou & Srivastava, 2007, pp. 23–25).

Within the service supply chain, there are many different types of activities that become crucial in the companies, including after-sales support. "After-sales support is the longest-lasting source of revenues to sellers and requires the smallest investment. Companies that ignore the after-market do so at their peril" (Cohen et al., 2006, p. 138). A notable example was General Motors, which received more profit from $9 billion in after-sales revenues in 2001 than they did from $150 billion of income from car sales (Cohen et al., 2006). One of the most practical activities in aftermarket activities is maintenance. The goal is to maximize the availability of the system with minimal cost.

6. Maintenance Supply Chain Characteristics

A maintenance supply chain involves the maintenance, repair, and overhaul organizations and the relationship within and across suppliers and customers; MRO organizations specialize in maintenance that "constitutes a series of actions necessary to restore or retain an item in an effective operating state" (Blanchard et al., 1995, p. 1). Maintenance supply chain characteristics are different from those of manufacturing supply chains. Cohen et al. affirm that industries such as automobiles, white goods, and others have sold so many units that service supply chains have become four or five times larger than the original equipment businesses (Cohen et al., 2006, p. 129).

When companies work with maintenance, the number of SKUs to manage is 15 to 20 times greater than when the industry manufactures a product. The demand of a manufacturing supply chain is predictable; on the other hand, the maintenance supply chain is unpredictable because many services are trigged when a failure occurs. Sometimes, scheduled maintenance is not an easy task to forecast. Because of the dynamics of the maintenance supply chain environment, inventory management uses pre-positioned resources to decrease the uncertainty. Manufacturing supply chains try to maximize resource velocity. The performance metric in manufacturing supply chains uses the degree of the fill rate, while the maintenance supply chain works with availability of equipment (Cohen et al., 2006, pp. 132–133) .

The maintenance environment includes components with a stochastic failure rate, different types of failures to be repaired, great numbers of spare parts for repair, and long

lead times to perform maintenance and to purchase spare parts. Frequently, maintenance does not incorporate fluctuations in equipment use, changes in environmental conditions, and equipment age (Jones, 2006, p. 18.1). The maintenance supply chain elements tend to be disconnected from each other, causing shortages and excesses of materials. All these factors can result in delays and high uncertainty in the maintenance process. A high level of uncertainty and lack of information integration cause excesses and shortages of spare parts. This misinformation causes low availability of aircraft, equipment, or systems, increasing costs.

Although there are similarities among manufacturing industries such as the traditional manufacturing process (e.g., shop-floor scheduling and assembly) (Gaudette, 2003), all involve suppliers, plants, and customers. There is significant difference between their manufacturing and maintenance supply chain characteristics, as shown in Table 4.

Table 4. Characteristics of manufacturer supply chain versus maintenance supply chain (after Gaudette, 2003; Ptak & Smith, 2011).

	Maintenance supply chain	Manufacturer supply chain
Process*	Requires special operational processes and skills, such as disassembly, inspection, testing, and repair	Manufacturing follows a logical sequence of production
Process Time	Stochastic time with variation	Fixed time with low variation
Routing**	Probabilistic time and occurrence of maintenance task	Manufacturing task is predictive and assembled with logical form
Inventory management**	High level of uncertainty inherent in the maintenance process and unique in corrective maintenance	Fixed material quantity to attend to final product assembly
Bill of material	Probabilistic with no fixed material and quantity	Fixed quantity
Variability of demand	Based on use of equipment and failure rate distribution	Based on the expected consumption of the consumer
Lead time	More uncertainty because items can be obsolete or no longer manufactured	Suppliers known, agreements and contracts are done more predictably
Supply chain	More organizations and clients to connect	Supplier directly connected to the organization

Cohen et al (2006) suggest that companies have to develop specific frameworks to manage this environment. They suggest some actions to manage this environment:

- Identify the product: a spare part with supplier identification is a hard task.
- Design a portfolio of service products: companies must prioritize a service and offer different business models based on service priority. For example, in a TV after-sales problem where customers pay for support that they need, and the priority is very high, the companies can use performance-based logistics and customers will pay based on performance.
- Determine after-sales structure: companies have to develop specific structures with a focus on visibility of information, incentives, and service.
- Design and manage after-sales services supply chain.
- Monitor performance continuously.

The different characteristics of the maintenance supply chain and manufacturer supply chain demonstrate the need to develop a specific framework for the maintenance environment.

> The majority of existing ERP software programs do not have the capability to manage complex service supply chain scenarios—where highly individualized service offerings are coupled with stringent response standards. Companies that apply ERP software without customizing the needs of this environment have bad experience and deliver poor service. (Cohen et al., 2006)

This research seeks to build a framework for companies that have maintenance as their business, in order to match demand with inventory need for preventive and corrective maintenance. These actions help the companies increase their capability to attend to the client. Therefore, it is necessary to understand the maintenance characteristics to build a framework for the maintenance supply chain.

B. MAINTENANCE MANAGEMENT

The discussion of the research is about information in maintenance environment. The following discussion explain the concept, main activates and definitions, the inventory models used in the maintenance, and the challenges in this area.

1. System Life Cycle

To understand where the maintenance supply chain is located, it is necessary to understand the system life cycle. A system "comprises a complex combination of resources integrated in such a manner as to fulfill a designated need" (Blanchard, 2003b, p. 8). The first step in creating a system is to identify the limits of acceptability for any system that is delivered to the user (Jones, 2006). The life cycle of any system has phases that relate to the customer requirements and the needs of the supplier. Each phase of the life cycle of a product has different interactions with the customer and supplier. Blanchard cited four phases for the system development cycle, shown in Figure 5.

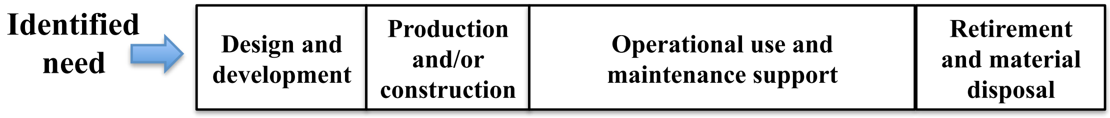

Figure 5. The system life cycle (from Blanchard, 2003b).

The first phase is related to matching the requirement of the user and system/product design and development. In this phase, there are many interactions with the customer and supplier. In this phase, the engineers are responsible for the maintenance concept, product planning, and system design (Blanchard et al., 1995; Blanchard, 2003a).

The second phase is the production phase. All the elements of the system or product are produced, tested, and put into full-scale operational use. This phase supplies information to maintenance and system requirements to verify if the system has been produced with the same characteristics that were planned (Blanchard, 2003b, p. 104).

System utilization and sustaining maintenance and support comprise the third phase. In this phase, the system is fielded, and there are continuous analyses of the use of the product. Depending on the situation, the product may have to be modified, the maintenance planning may have to change, and, in some cases, new products may need to be developed. The purpose is to assess the actual performance and effectiveness of the system to ensure that all requirements are being met (Blanchard, 2003b, p. 106). The final phase is retirement, which specifies the material phase-out and recycling.

In each aforementioned phase, the relationships between the customers and suppliers are different. In the first phase, the relationship is more focused on finding the supplier and agreeing on the specifications. In the second phase, the suppliers send the material or product to assembly or production of the system. In the third phase, the suppliers can send material or some suppliers perform maintenance. In the last phase, the item is retired and many recycling projects are needed.

This summary only represents a small picture of a system/product life cycle. In reality, there are many processes and tasks to develop a system. For further information,

the reader can read deeply in Blanchard (2003b) or Jones (2006). This researcher will study more specifically the third phase of the life cycle. As Blanchard wrote, “this phase indicated that a large percentage of the total life-cycle cost for a given system is attributed to operation and maintenance activities (e.g., up to 75 percent for some systems)” (Blanchard, 2003a, p. 24).

2. Maintenance

According to Blanchard et al. (1995, p. 15), “maintenance is all actions necessary for retaining a system or product in, or restoring it to, a desired operational state.” Preferably, maintenance is required to maintain the system running efficiently enough to at least meet the initial customer requirements (Blanchard, 2003b, p. 105). There are different types of maintenance that help to extend system life. Each offers advantages and disadvantages depending on the situation.

a. Maintenance Category

There are different categories of maintenance programs:

- **Corrective or reactive maintenance**: this type of program is used only when the equipment breaks down. This includes all unscheduled maintenance to restore the system to a specific condition (Blanchard et al., 1995, p. 15). As an advantage, it is low cost and requires less staff because the manager does not expend money on personnel or support equipment. However, it has a lot of disadvantages, because unplanned downtime of equipment increases cost and labor cost. The life cycle is shorter and results in more frequent equipment replacement. Because it does not have formal planning, the resources are used more inefficiently (National Aeronautics and Space Administration, 2000). Unscheduled maintenance may be measured in terms of frequency (MTBMu) or elapsed time (Mct or MTTR) (Blanchard et al., 1995).
- **Preventive Maintenance**: this type of program is performed to avoid failures and extend the life cycle of the system. It includes all scheduled maintenance actions performed to retain a system or product in a specified operational condition (Blanchard et al., 1995, p. 15). It covers periodic inspections, condition monitoring, critical-item replacement, periodic calibration, and the like. Scheduled maintenance may be measured in terms of frequency (MTBMs) and elapsed time (Mpt). Many pieces of equipment have a time between overhaul (TBO) or a scheduled program of maintenance (e.g., cars with maintenance programming based on miles,

aircraft with maintenance programming based on hours flown) (Blanchard et al., 1995, pp. 16–17). Studies indicate that this maintenance can save 12 to 18 percent over reactive maintenance (Sullivan, Pugh, Melendez, & Hunt, 2010, p. 53). Preventive maintenance can decrease the number of failures, providing costs, and energy savings.

- **Predictive Maintenance**: the objective is this type of maintenance program is to predict when the failures will occur and to take preventive measures accordingly. Measurements detect degradation results in preventive maintenance. It differs from preventive maintenance, basically, in that preventive is performed based on a period of time, and predictive maintenance is executed based on the condition of the system. Studies indicate that this can save 8 to 12 percent over preventive maintenance (Sullivan et al., 2010, p. 5.4). This maintenance increases availability, decreases downtime, and decreases cost, but managers have to invest more in diagnostic equipment and staff training.
- **Reliability-Centered Maintenance**: this type of maintenance program ensures that equipment is reliable, which is a major goal of any development program; but it is impossible to produce a design that does not eventually break. To promote reliable systems, reliable-centered maintenance (RCM) was developed. The purpose of RCM is to identify maintenance that can be done on a scheduled basis to avoid unwanted and untimely failures and improve overall system reliability and, therefore, system availability. In other words, fix an item within a system before it breaks and renders the system inoperable. RCM is applied to develop a cost-effective scheduled maintenance program (Jones, 2006). The philosophy is that the equipment of a system is not composed of items of identical importance. The resources are concentrated on critical items; this politics permits a facility to match the resources to needs while improving reliability (Jones, 2006, p. 8.3).

b. Maintenance Level

Maintenance level pertains to the division of functions and tasks for each area where maintenance is performed. Depending on the place and operation, the system can be maintained in different ways. Factors such as task complexity, personnel skill-level requirements, frequency of occurrence, special facility needs, economic criteria, dictate to a great extent the specific functions to be accomplished at each level. By following Blanchard (1995), this research will use these maintenance levels:

1. **Organizational maintenance**: is performed at the operational site (e.g., airplane, vehicle, manufacturing production line). Operational-level personnel are usually involved with operation and use of

equipment/software and have minimum time available for detailed system maintenance. The maintenance tasks at this level generally are equipment performance checks, visual inspections, cleaning, and the removal and replacement of some components. Personnel at this level do not repair the equipment but forward it to the intermediate level (Blanchard, 2003b, pp. 54–55; Blanchard et al., 1995, pp. 151–153).

2. **Intermediate maintenance**: "tasks are performed by mobile and/or fixed specialized organizations and installations." At this level, the maintenance personnel can remove or replace end items, major components, assemblies, or piece parts. Generally, it takes specific skills of mechanics and better test equipment to enable greater levels of repair of the equipment, repair to the module and piece-part level (Blanchard, 2003b, p. 56; Blanchard et al., 1995, p. 153).

3. **Depot, supplier, or manufacturer maintenance**: is the most specialized and highest maintenance level that supports the execution of complex tasks above the intermediate level. This maintenance includes "the complete overhauling, rebuilding, and calibration of equipment as well as the performance of highly complex maintenance actions" (Blanchard, 2003b, p. 57; Blanchard et al., 1995, pp. 153–154).

c. Repair Classification

Repair policy serves to define whether the item will rate a maintenance service. Repair policies are established in the initial period of system development, but throughout the life cycle of the item, the criteria are improved and changed (Blanchard, 2003b, p. 57).

Generally, a system is a set of subsystems and components. The policies define which components can be maintained or which components can be replaced or discarded. Many times, this is the result of analysis of cost and reliability (Blanchard, 2003a, p. 142). Blanchard (1995) explains the following divisions to categorize repair policies:

- A nonrepairable item "is generally modular in construction with relatively low replacement and disposal cost, and is discarded when a failure occurs." Usually, this kind of item can be discarded and is replaced when it fails without maintenance (p. 154).
- A partially repaired system may offer different options. Generally, the policy depends on the operational requirements and operational availability. If there is a need for high availability, the item can be replaced quickly on one level and sent to the depot to be repaired. In the

same situation, the availability factor could be not so high that mechanics can search for the failure and perform maintenance (p. 157).

- Fully repairable systems consist in large logistic support in terms of testing, maintenance, and supply. This concept involves levels of maintenance, functions within the levels of maintenance, types of maintenance tasks in each level, effectiveness factors (e.g., MTBM, MDT, Mct, Mpt), types of monitoring, support equipment, and control of the system (pp. 158–159).

3. Performance Measurement

Performance measures of a system are essential. This section explains some system performance measures used in the maintenance environment.

a. Reliability

The reliability of a system and its components will fluctuate throughout their development, production life cycle, and operation (Kang, 2012). Reliability can be defined as the probability that a system or product will perform in a satisfactory manner for a given period of time when used under specified operating conditions in a given environment (Blanchard et al., 1995, p. 13).

Reliability can be linked with system failure or success. System failure is related with frequency of inherent failure or system failure. System success is the probability of system success (Jones, 2006, p. 4.3). Let T be a random variable that represents the time until next failure (or the time between failures), and f (t) be the probability density function, and F(x) the cumulative density function of T. The reliability function, R (t) is defined as

$$R(t) = \Pr(T > t) = \int_t^\infty f(x)dx = 1 - F(x) \tag{2.1}$$

R (t) is the probability that the failure will not occur until time t. If T is an exponential random variable, the reliability function R(t) is (Kececioglu, 1991, pp. 62–64).

$$R(t) = \Pr(T > t) = \int_t^\infty f(x)dx = \int_t^\infty \lambda e^{\lambda x}dx = e^{-\lambda t} \tag{2.2}$$

If the system follows exponential distribution, the failure rate is relatively constant during the mature stages of a system life cycle, as shown in Figure 6.

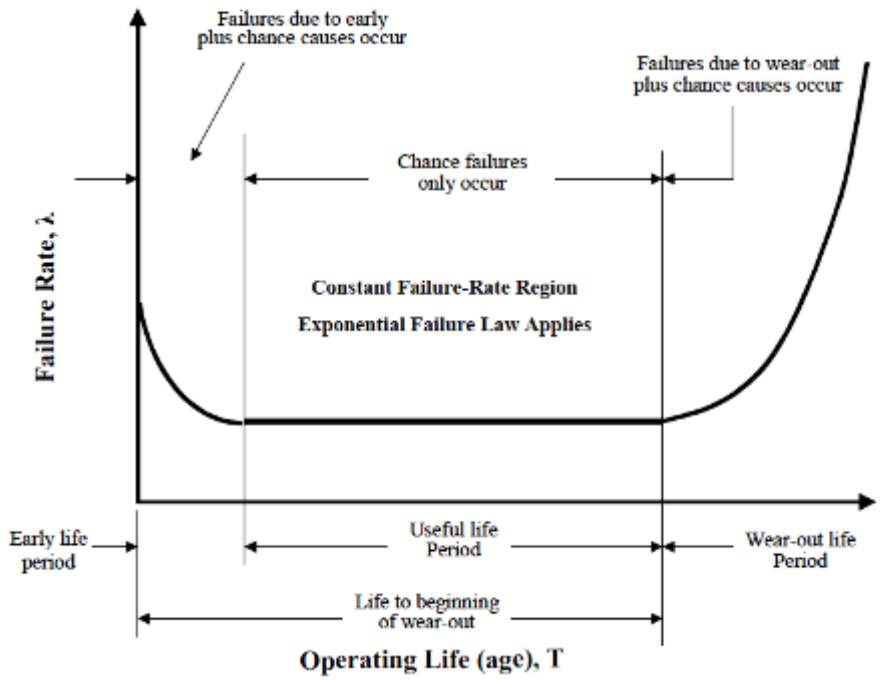

Figure 6. Reliability bathtub curve (from Kececioglu, 1991).

The failure rate of a system indicates the anticipated frequency that a failure will occur and can be represented according to (Jones, 2006, p. 4.4) as:

$$\lambda = \frac{Number\ \ of\ \ failures}{Total\ \ measured\ \ usage} \tag{2.3}$$

Another measure of reliability can be defined as mean time between failures (MTBF). The calculation uses the same failure rate defined in Equation 2.3. MTBF is the probability of satisfactory performance during a given period under specified operating conditions (Kececioglu, 1991, pp. 206–207):

$$MTBF = \frac{1}{\lambda} \tag{2.4}$$

where λ is referred as the failure rate.

b. Maintainability

According to Blanchard et al., “Maintainability is the ability of an item to be maintained” (Blanchard et al., 1995, p. 1). An item that allows for maintenance easily, accurately, safely and economically has good maintainability. The principles of maintainability can be applied to large or small systems. If the system incorporates good maintainability characteristics in the project and design, the life-cycle cost can be reduced significantly.

Maintainability can be expressed in terms of maintenance frequency factor (e.g., how many times an item needs maintenance in a time cycle), maintenance time and labor hours (e.g., how long is the time of maintenance of the item, or how many hours spent to do maintenance), and maintenance cost (e.g., how much is the maintenance cost).

All these factors can be measured with a combination of measurements:

- Mean time between maintenance (MTBM): this factor includes preventive (scheduled) maintenance that can be called time between overall (TBO) and corrective (unscheduled) maintenance requirements. If the TBO is not applicable, the MTBF is MTBM (Blanchard et al., 1995, pp. 111–112; Jones, 2006, p. 4.19).
- Mean time between replacements (MTBR): occurs when the maintenance task usually generates spare parts. It can be scheduled (MTBSR) or unscheduled (MTBUR). This factor is greater than MTBM and is a “significant input to spare part requirements analysis” (Blanchard et al., 1995, p. 112).
- Maintenance Downtime (MDT): is the total elapsed time required to repair and restore a system to full operating status. It includes mean time to repair (MTTR) of corrective and preventive maintenance, logistics delay time (LDT), and administrative delay time (ADT) (Blanchard et al., 1995, p. 109).
- Maintenance man-hours per system/product operating hour (MMH/OH): this represents the hours of maintenance used in the maintenance of the system (Blanchard et al., 1995, p. 114).
- Maintenance cost per system/product operating hour (Cost/OH): this cost must be considered in the context of life-cycle cost (LCC) of the system (Blanchard et al., 1995; Kang, 2012, p. 2).

c. Availability

The measure to check if the system is always ready to use is availability. According to OPNAVINST-3000.12A, "It has been defined as the ability of a product/system to be ready for use when the customer wants to use it" (Department of the Navy, 2003, p. 10).

Generally, the combination of good maintainability and a reliable system produces good availability of the system. Availability (Ao) is a probability function of reliability, maintainability, and supportability of the components.

$$A_o = \frac{System\ UpTime}{Total\ Time\ \ (UpTime + DownTime)} = \frac{MTBM}{MTBM + MDT} \tag{2.5}$$

Total time has two sub-factors, UP time and DOWN time. UP time is the time a system is operational between failures. DOWN time is the time the system is not operational (Department of the Navy, 2003, p. 1).

Another measure relating to availability is readiness risk, which is when the operational availability goes below a critical threshold value, or Pr (Ao<c) (Blanchard et al., 1995, pp. 126–128).

4. Inventory Models for Maintenance

Spare parts are required to sustain scheduled and unscheduled maintenance. The objective of provisioning and supply support is to have the material available when and where needed in the quantity needed to support maintenance. The author uses the Jones (2006) definition for spare parts. According to Jones:

> The term spare parts will be used to refer to all parts required for maintenance whether the parts are spare (repairable items), repair parts (items that are nonrepairable and are discarded when they fail), or consumable (items that are consumed when used, such as gasket material or adhesives). (Jones, 2006, p. 18.1)

a. Inventory Theory

Giere (1991) affirms that, for a model to become a theory, hypotheses are used to make the relation between the real world and model. Thereafter, models are used to make

predictions using reasoning or calculation. Experimentation and observation are used to measure the data. This way, the experiment can check if a model fits the real world and if a hypothesis is true or not (Giere, 1991). Generally, operations research begins by formulating the problem, and generally, building a model that represents the reality. The model is hypothesized for validation in the real situation (Hillier & Lieberman, 1980, p. 4).

> The purpose of inventory theory is to explain the rules that management can use to minimize the costs associated with maintaining an inventory and meeting customer demand. (Winston, 1994, p. 867)

This theory addresses the frequency and size of an order. This theory fits Giere's definition of a scientific theory, where Giere (1991) affirms that theory has two components. One component, the inventory theory, has many models, such as deterministic models (e.g., economic order quantity (EOQ) model) and stochastic models. The second of Giere's components is the theoretical hypothesis that selects facts in the real world about which one or more models can make some predictions (Giere, 1991). "Several complex inventory models have been formulated in an attempt to fit such situations, but they still leave a wide gap between practice and theory" (Hillier & Lieberman, 1980, p. 539).

In any company, it is necessary to hold inventory for a variety of reasons, such as varying client demand, uncertainty among the elements of the supply chain, and varying lead times of suppliers. These uncertainties lead to maintaining goods to respond to the client (Ballou & Srivastava, 2007, pp. 338–339; Simchi-Levi et al., 2007, p. 31). Inventory theory seeks to minimize cost and match the client demand (Ballou & Srivastava, 2007, pp. 345–346). The theory works with product availability and relevant cost, and is described in the following paragraphs.

(1) Product Availability

This component seeks to satisfy the client demand. This component is referred to as "the probability of fulfillment capability from current stock." This is known as the service level or full rate and can be defined as (Ballou & Srivastava, 2007, p. 346).

$$SL = 1 - \frac{Expected\ number\ of\ units\ out\ of\ stock\ annually}{Total\ annual\ demand} \tag{2.6}$$

Another measure for availability is safety factor that is the probability of being in stock during the lead-time period or the probability of finding an item in stock when it is needed. In reality, this number is the number of standard deviations from the mean of the demand of lead time (Ballou & Srivastava, 2007, p. 360; Simchi-Levi et al., 2007, p. 43). The safety factor that can be chosen from a statistical table that represents the probability of stockout during lead time is:

$$z = 1 - \alpha \tag{2.7}$$

Depending on the inventory policy, organizations can use different formulas for safety stock. There are many situations of selecting the safety stock value z (e.g., equal times supplies, fixed safety factor, cost per stockout occasion, and fractional charge per unit short per unit time). Readers interested in this issue can go to Simchi-Levi et al. (1998, pp. 241–274). The author will discuss two situations: shortage penalty based on backorder cost per unit and lateness charge per unit.

Shortage penalty per backorder cost per unit is based on the cost to mitigate the shortage. The penalty occurs only when there is a shortage; if the material is missing in two periods, the penalty will be charged only in the first period. The formula to find Z that minimizes the inventory cost with the shortage cost is:

$$Z = 1 - \frac{h * Q}{S * D} \tag{2.8}$$

where h is holding cost, Q is the lot size, S is shortage cost per unit, and D is demand.

Another shortage penalty is the lateness charge per unit. This occurs every time there is a shortage of material. In the previous example, if the item is missing in two periods, the shortage cost will be charged in the two periods. To find the value of z with a loss rate that balances the shortage and holding cost, there is a need to find the value $E_{(z)}$; that is called the unit normal loss integral as a function of the normal distribution:

$$E_{(z)} = \left(\frac{h}{s + h}\right) * \frac{Q}{\sigma_{LT}} \tag{2.9}$$

where σ_{LT} is standard deviation of mean during the lead time (Silver et al., 1998, p. 266).

To find the value of $E_{(z)}$ we use the formula (Ballou & Srivastava, 2007):

$$E_{(z)} = f(z) - z*(1-F(z)) \tag{2.10}$$

where $f(z)$ is the point probability at z and $F(z)$ is the cumulative probability at z.

If we find the value of $E_{(z)}$, it is possible to find the value of the service level with Equation 2.11 (Ballou & Srivastava, 2007, p. 362).

$$SL = 1 - \frac{\sigma_{LT} E_{(z)}}{Q} \tag{2.11}$$

Given an example where Q=200, σ_{LT} =40 and the probability in stock during lead time = 75 percent

Z=Normal.Inv (0.75)=0.67

then:

$$E_{(z)} = f(z) - z*(1-F(z))$$

$f(z)$ =NORMAL.S.DIST(0.67,0)=0.318

$F(z)$=NORM.S.DIST(0.67,1)=0.748

$$E_{0.67} = 0.318 - (0.67*(1-0.748)) = 0.150$$

$$SL = 1 - \frac{40*0.150}{200} = 0.9625$$

The service level and safety factor are important components to calculate the order quantity. The problem of the service level is that these parameters calculate only the probability quantity for an item. If a system needs five items, and the service level parameter is 95 percent, the probability of that filling the entire need without any item being out of stock will be:

$$0.95 * 0.95 * 0.95 * 0.95 * 0.95 = 0.77$$

The system has only a 77 percent of probability of completing the need. If the quantity of part numbers increases, the probability of stockout increases significantly (Ballou & Srivastava, 2007, p. 346).

(2) Relevant Costs

Ordering cost is associated with cost to replenish an order. When an order is placed, this cost is derived from the costs of processing, setting up, transmitting, handling, and purchasing the order. Some of the components of order costs are fixed (e.g., costs of transmitting and processing an order), while others may vary with size (e.g., costs of transportation and material handling). This cost can be expressed as the cost of placing an order multiplied per quantity of order in a period (Ballou & Srivastava, 2007, p. 348; Forsythe, 1976, pp. 102–103; Hillier & Lieberman, 1980, p. 494; Simchi-Levi et al., 2007, pp. 33–34).

Holding cost, also referred to as inventory carrying cost, "is accumulated per unit held in inventory per day that the unit is held" (Simchi-Levi et al., 2007). Ballou (2007) affirms that 80 percent of holding costs is referred to as capital cost. The other 20 percent of the cost is divided by space cost (volume inside the storage), inventory service cost (insurance and tax), and inventory risk cost (deterioration, obsolescence) (Ballou & Srivastava, 2007, pp. 348–349; Vollmann et al., 2005, p. 138). This research will use annual holding cost per unit.

Shortage cost occurs when demand exceeds the available inventory for an item (Vollmann et al., 2005, p. 139). It is related to the level of customer service that the organization wants to reach. It can be like a missed chance of profit, which is called the opportunity cost. The quantity of shortage is an important measure to assessing inventory performance. As an example, consider two different shortage costs: lost sales costs and back order costs. A lost sales cost occurs when the client cannot buy the item because of a shortage, and the client decided to remove the request for the item. Generally, the client purchases the item from another vendor. Back order cost occurs when the client will wait for the item that it is not in stock (Ballou & Srivastava, 2007, pp. 349–350).

Other costs, such as revenue cost, generally are not included in the models; it is assumed that the price and demand for the item are not under control. Salvage cost is associated with the disposal of an item. It can be combined with excess of supply over demand (Hillier & Lieberman, 1980, p. 495). The cost components presented represent the main factors that are presented in various models of inventory control.

There are many methods for classifying the inventory models, but usually the models are classified by the nature of demand: whether the demand for a period is known (deterministic models) or unknown but follows a probability distribution (stochastic models) (Hillier & Lieberman, 1980, p. 496).

b. Deterministic Models

Deterministic models are usually models used in inventory models. These models are large used in many areas. The following explanation shows that formulas and use the models

(1) Economic Order Quantity

Economic order quantity (EOQ) was created by Harris (1913) and disseminated by Wilson (1934) to minimize total cost. This is one of the earliest and most well-known results of inventory theory (Silver et al., 1998).

The assumption of this model is that demand and lead time are constant, shortage is not permitted, the cost factors do not change with time, and the entire order quantity is delivered at the same time (Silver et al., 1998).

The total cost expressed per unit time is: Cost/Unit time= Fix Cost + Product Cost + Holding Cost:

$$TC = \frac{D * k}{Q} + Dc + \frac{hQ}{2} \tag{2.12}$$

where Q = order sizes in units, D = total demand in unit period, T = length of the period; H = cost of holding one unit, per period of time, K = cost of placing an order, and c = cost of production.

Setting to zero the derivative of TC in function of Q gives:

$$\frac{dTC}{dQ} = \frac{D * k}{Q^2} + \frac{hQ}{2Q} = 0$$

Solving the equation, it finds the Economic Order Quantity (Q)

$$Q = \sqrt{\frac{2DK}{h}} \tag{2.13}$$

(2) Shortages Permitted

This model is used when shortages are allowed to be backordered. This model seeks to minimize the cost related with the shortage. “It may be profitable to permit shortages to occur because the cycle length can be increased with a resultant saving in setup costs” (Hillier & Lieberman, 1980, p. 499)

Cost/Unit time= Fix Cost + Product Cost + Holding Cost + Shortage Cost

$$TC = \frac{D * K}{Q} + Dc + \frac{hD^2}{2Q} + \frac{p(Q-S)^2}{2Q}$$

where p is the shortage cost and S is the maximum level of stock at the beginning of a cycle.

To find the optimum values of S and Q, derive the equation in function of S and Q:

$$S = \sqrt{\frac{2DK}{h}}\sqrt{\frac{p}{p+h}} \tag{2.14}$$

$$Q = \sqrt{\frac{2DK}{h}}\sqrt{\frac{p+h}{p}} \tag{2.15}$$

(3) Continuous Review Policy

The inventory is reviewed continuously, and an order is placed when the inventory reaches a particular level, the reorder point. This policy is known as (Q,R) policy whenever the inventory level falls to reorder point R, and an order is placed for Q units. It is appropriate when there is a computerized inventory system to trigger the orders. The reorder point (ROP) is used to cover the lead time of the item(Silver et al., 1998; Simchi-Levi et al., 2007).

$$ROP = D * Lt \tag{2.16}$$

where D is the demand during a period and Lt is the average of lead time during the same period. When the inventory reaches the ROP, an order Q is replenished.

(4) Other Models

There are many other models, such as quantity discount models, where the model combines the quantity of a discount price that depends on the amount ordered (this means that the unit cost varies with the quantity ordered), models that compute the inflation to decide the order quantity, models that assign order restrictions based on criteria such as the perishability of the item, models that depict the minimum quantity allowable, and models that compute finite replenishment rates and freight discount costs (Hillier & Lieberman, 1980, p. 501).

These models seek to reproduce the typicality of each inventory characteristic. Many authors describe these models; some notable ones include Porteus (2002), Silver et al. (1998), and Hillier and Lieberman (1980).

c. Stochastic Model

In the real world, it is hard to achieve stable and constant demand. Generally, many factors bring uncertainty to demand and complicate forecasting. The stochastic models seek to mitigate the uncertainty and better attend to the demand. The stochastic model works with probabilistic distribution of demand (e.g., discrete demand, discrete cumulative demand, continuous demand probability, continuous cumulative or the standard normal distribution function). According to Jensen and Bard, "An important modeling decision concerns which distribution to use for demand" (Jensen & Bard, 2002).

(1) Single-Period Models

The models have to meet an uncertain demand of a specific period with only one time order. The challenge is how much to order to match the demand in a period to decrease excess or shortage. This model addresses situations that have a short and defined shelf life (Ballou & Srivastava, 2007, pp. 352–353; Simchi-Levi et al., 2007, p. 36).

To find the best quantity to order (Q), the model uses marginal economic analysis. Q is found at the point where the marginal profit on the next unit sold equals the marginal loss of not selling the next unit (Ballou & Srivastava, 2007, pp. 352–353). The marginal profit per unit is:

Profit=Price per unit – Cost per unit

The per-unit loss is:

Loss= Cost per unit – Salvage value per unit

Considering the probability of a given number of units being sold, the expected profits and losses are balanced at this point:

$$CP_n(loss) = \frac{1 - CP_n}{\Pr ofit}$$

CP_n is the cumulative frequency of selling at least n units of the product, solving the previous expression for CP_n:

$$CP_n = \frac{\Pr ofit}{\Pr ofit + Loss} \tag{2.17}$$

Another form to calculate the quantity is in the function of the cost components and using the normal distribution parameters:

$$Q = \mu + K\sigma$$

The optimal condition occurs when:

$$\phi(k) = \frac{b - c + d}{b - a + d} = \frac{p - c}{p + h} \tag{2.18}$$

where a=salvage value, b=selling price, c=purchase cost, d=penalty cost, p=shortage cost, h=holding cost (Jensen & Bard, 2002, pp. 25.19–25.22).

So if the mean is 200 and the standard deviation is 30, if the $\Phi(k)$=0.7895, K is normal inverse (0.7895) = 0.805, so

$$Q = 200 + 0.805 * 30 = 224.15 = 225$$

This is the famous newsboy problem, where the newsboy has to decide the quantity to purchase for the day.

An example is a military operation. A company will do the maintenance of a specific repairable during the operation. The company has to predict the material necessary to conduct the maintenance in the operation during a specific time. In this case, there is a time restriction in the operation during which the company cannot replenish material. To be repaired, the machine needs spare parts. If the company does the maintenance, the company charges $100,000 for the repair. The company pays $80.00 for each kit of spare parts. If the kit of spare part needs to be returned, the supplier pays $60.00 (Ballou & Srivastava, 2007, pp. 352–353). The failure distribution during the operation is shown in Table 5.

Table 5. Failure distribution.

Number of failures	Frequency	Cumulative
0	0.05	0.05
1	0.20	0.25
2	0.23	0.48
3	0.32	0.80 <= Q
4	0.15	0.95
5	0.05	1.00

The best CP_n is:

$$CP_n = \frac{\Pr ofit}{\Pr ofit + Loss} = \frac{(100-80)}{(100-80)+(80-60)} = 0.50$$

The CP_n value is between two and three failures. Rounding up, the best prediction is that failure will occur three times. There are other formulations of a single-period model, such as fixed ordering cost using uniform and exponential distribution.

(2) Continuous Review Policy

The order quantity follows Equation 2.13 used in the previous section. ROP is different because it incorporates into the model the demand uncertainty during lead time

through a safety stock (SS). The SS represents the quantity of material needed to protect against deviations (standard deviation, STD) from average demand during lead time (Simchi-Levi et al., 2007, pp. 42–43):

$$SS = z * STD * \sqrt{Lt} \tag{2.19}$$

(z) “is that number the standard deviation from the mean during lead-time to a desired probability of being in stock during the lead time period (P)” (Simchi-Levi et al., 2007, p. 42). The reorder point is:

$$ROP = Lt * D + z * STD * \sqrt{Lt} \tag{2.20}$$

When there is lead time uncertainty, the safety stock change to incorporate this parameter:

$$SS = z * \sqrt{Lt * STD_D^2 + D^2 * STD_{Lt}} \tag{2.21}$$

(3) Periodic Review Policy

This policy reviews the inventory level in a period. This policy is preferred when the inventory control is manual, when a large number of items come from the same vendor/supplier, when items need predictability, and when there is transportation savings when ordering items at the same time (Ballou & Srivastava, 2007, p. 368). This policy is known as (Q,S) policy where there are two inventory levels, s and S. During each inventory review, if the inventory position is below s, there should be an order to complete the quantity to S.

This model uses s as the reorder point. For Q, the EOQ model, thus S=R+Q. Q uses the same formula for EOQ. For ROP it is:

$$ROP = T * D + z * STD * \sqrt{T + Lt} \tag{2.22}$$

T is the period of inventory review. This model protects against the uncertainty during lead time and the period of inventory review.

(4) Advanced Models

The complexity of the problem when the demand follows a known probability distribution forced many researchers to develop sophisticated models to represent

realistic cases. Models to adequately show the different fulfillment service levels of the customer or models that focus on the availability of systems are among the diverse models developed in recent years.

Some models focus on the availability of a system. Sherbrook (2004) developed a model that focuses on optimizing the availability of the end-item (such as aircraft) and then determining the appropriate inventory policies. The Multi-Echelon Technique for Recoverable Item Control (METRIC) models focus on the repairable items with aspects of modeling multi-echelon architecture to maximize the availability of the system (Sherbrooke, 2004).

Muckstadt (2010) improves the VMETRIC models (called MOD-METRIC) that establish what inventory (repairable item) will be required to meet operational requirements. His work answers the question “how much do I need of each part type to meet my goals, given the nature of the resupply network?” (Muckstadt, 2010).

Another important element in the stochastic environment is multi-echelon inventory. This supply chain presents many elements connected by many degrees of separation. Because of these separations, demand variation among the elements often produces significant instability in the chain, leading to a bullwhip effect (Sterman, 2000). Some models try to minimize this effect. There are models for deterministic demand (such as sequential stocking point with level demand), multi-echelon stocking points with time-varying demand, models for probabilistic demand (such as the arborescent system that seeks to centralize the inventory control), and mechanisms such as vendor-managed inventory (VMI) that centralize the control (Silver et al., 1998).

Silver at al. (1998) present a selection of various models to make decisions in different situations, such as different shortage costs, fraction of demand satisfied directly from shelf, allocation of a total safety stock to minimize the expected total value of shortage, and many others types. Readers interested in further topics of stochastic inventory can consult Silver et al. (1998) and Porteus (2002).

5. Challenges in Maintenance Management

Maintenance management is not an easy task because of the risk of failure (Cohen et al., 2006). Many techniques have been developed to reduce the uncertainty related to maintenance management (e.g., preventive and predictive maintenance), but the challenge to increase system availability remains. The researcher has discussed the maintenance puzzle by focusing on three areas: demand, maintenance tasks, and inventory.

The maintenance demand is hard to predict because "demand of repairs crop up unexpectedly and sporadically" (Cohen et al., 2006, p. 131). Each type of repairable has a different failure distribution. It means that for each item, managers have to do a particular prediction. But, for forecast, managers need equipment data from the client, and that information often is not available because of poor data accurate (e.g., the client does not monitor of collect the information correctly) (Cohen et al., 2006, p. 131). Maintenance often occurs when failures happen, so this is a reactive system that seeks to respond to a situation. The proposed model of research tries to change this situation by transforming the system to a pull system and adopting forward-thinking planning.

Although preventive maintenance has defined tasks, many times degradation or failures can occur and unscheduled tasks happen. Corrective maintenance does not have a specific bill of material, so any spare part can be changed in this maintenance. The failures do not have a standard cause and, for each failure, the maintenance tasks and spare part to fix the equipment can be different. There is no accurate bill of material and scheduled maintenance for which to plan. In this situation, the uncertainty increases significantly. This research seeks to link the elements of the maintenance supply chain to create a database of spare part that responds to unexpected maintenance.

When maintenance management cannot predict the demand and the spare part needed to attend to the demand, maintenance management is faced with another and even greater challenge—determining which and how many spare parts to keep available to attend to the need. The quantity of items to manage is 15 to 20 times more than that needed in the manufacturing environment of the same equipment and difficult to obtain

promptly from suppliers (Cohen et al., 2006; Higgins, Brautigam, & Mobley, 1994, p. 2.114). Besides this fact, there is the difficulty of predicting when and how many spares are necessary. Then, to decrease cost, inventory management is a great challenge. This study seeks to identify the spare part need based on maintenance planning. The capability to share and integrate information across the elements of the maintenance supply chain is critical to the effectiveness and efficiency of this new maintenance planning.

C. ENTERPRISE RESOURCE PLANNING

This section links supply chain and information sciences by explaining ERP/MRP that can be used in the both areas. The author analyzes the evolution, theories, and concepts, about ERP/ MRP in the maintenance area.

1. Supply Chain and Information Sciences

It has been said that "uncertainty and risk are inherent in every supply chain" (Simchi-Levi et al., 2007, p. 3), and that "information technology is a critical enabler of effective supply chain management" (Simchi-Levi et al., 2007, p. 14); thus, there is a relationship between these aspects of SCM that needs to be discussed.

As the name indicates, information science is the study of information and its relations. Nonaka and Takeuchi explain that "information is a flow of messages" (Nonaka & Takeuchi, 1996). Barabasi formulated that everything is connected in some degree of separation (Barabási, 2003). If information is a flow, and everything is connected and passes some messages, then information science is a huge field to study. For a narrower focus, information science can be defined as a science that studies the relation of information among sciences. Using this example, it can address the intersection of supply chain science and information sciences.

Supply chain science studies the network of processes and stock points used to deliver goods and services to customers (Hopp, 2011). If we think of a network, supply chain science studies the relationship among the elements of the supply chain within and across companies. On the other hand, information sciences has a subset that examines the process of developing and using information and communication technologies within

organizations (Avgerou, 2000). We can see that supply chain science focuses more on the process itself and information science concentrates on the information or communication of information in the process; therefore, one science complements the other science.

This concept is very important because a supply chain generally has high information variability and poor visualization of information. This means that if a supply chain has uncertainty and dynamism, availability of information is critical to SCM, and information sciences can help managers determine what information to collect, how to collect it, and how to analyze and use it.

There is a concept that can work equally well in SCM as it does in information science: enterprise resource planning (ERP). Vollmann et al. (2005) presented two interesting definitions about ERP. For the information technology community, "ERP is a term that integrates the application program in finance, manufacturing, logistics, sales and marketing, human resources, and the other functions in an organization." From the manager's view, "ERP represents a comprehensive software approach to support decisions current with planning and controlling the business firm" (Vollmann et al., 2005, p. 109). In other words, ERP is a term so comprehensive that it supports both the supply chain and information science areas. ERP seeks to integrate information of the organization through best practice functionality and systems interoperability with common databases and interfaces (Markus et al., 2000). Therefore, it is interesting to understand the ERP evolution.

2. Evolution of ERP

Enterprise resources planning is an offspring of a tool known as materials requirement planning (MRP), which is used to prepare a list of materials that the company has to buy or make in order to execute a production plan. This technique was developed in the 1960s and became a favored approach to managing manufacturing sites with the development of computers. Later, this technique evolved into what is called manufacturing resources planning (MRP-II), which uses an increasing amount of data to

manage the operation. As MRP-II expanded to incorporate additional enterprise data, more computer technology was used, more functions were integrated, and decision making was incorporated.

The MRP system's expansion to other types of business sectors, such as health care and financial institutions, made manufacturing a restrictive term that poorly described its potential, and so enterprise became the new designation to describe the system's capabilities. That is, today's ERP is an extension of the MRP of the past (Silver et al., 1998). ERP was an extension of MRP II that sought to integrate information and processes across the companies using the Internet. Nowadays, ERP systems have been installed in many businesses (Leary, 2004), and many software companies try to develop systems to support supply chain management.

In many business-to-business (B2B) relationships, ERP systems integrate the company's data with that of suppliers or customers. Management techniques, however, are in constant evolution, and variations of the ERP system have appeared, such as IRP (Internet), Cloud ERP, and Enterprise System. These new approaches integrate organization, industry, and government, and use many kinds of services such as mobile, wireless, and the Internet (McGaughey & Gunasekaran, 2007). In the latest concept, Cloud ERP, systems use cloud storage techniques to integrate all services (Suciu et al., 2011).

In summary, ERP is "a method that unifies all processes within an organization into one software system or database" (Chen, 2009). Large organizations adopt the ERP system to standardize their business processes (Butler & Pyke, 2003). It is expected that an ERP system integrates business processes to reduce cost and increase value in their process. This way, information is available to make effective decisions (McGaughey & Gunasekaran, 2007). Many times the ERP system replaces many existing systems and databases, aggregating information into a single unified process. ERP is not easy to install, adopt, and maintain, so organizations have to rely on proper system maintenance as ERP evolves (Salmeron & Lopez, 2012).

3. MRP Analyses

This section gives a technical discussion about the theories, characteristic, and how MRP works. It's important to discuss the weakness and challenge about this technique.

a. MRP Theory

Joseph Orlicky wrote in 1974 that material requirement planning has been started "not by theoreticians and researchers but by practitioners" (Ptak & Smith, 2011, p. 373). Orlicky wrote a study guide about MRP to collect all existing knowledge on the topic. MRP is a framework that integrates information within and across the companies to support decisions. MRP can be considered "a management information system rather than a decision-making system" (Baker, 1993, p. 571).

MRP is related to a planning and control system. MRP helps the managers make decisions with acquisition and production scenarios (Baker, 1993; Vollmann et al., 2005). MRP uses the information from the master production schedule (MPS) that tells what the company intends to produce, the bill of material (BOM) that supplies information about the material needed to produce the deliverable, and inventory status that shows what material the company has on hand. With these information resources, MRP generates information about what the company has to produce (shop orders) and which materials it has to buy (purchase orders) (Baker, 1993; Ptak & Smith, 2011; Vollmann et al., 2005).

According to Ptak and Smith, "academicians considered the study of MRP vocational rather than scientific" (Ptak & Smith, 2011, p. 375). An MRP theory has been developed during the last 25 years by some researches which seek to develop a mathematical model to describe MRP. Grubbström has written the first articles about the theory. He uses a gozinto graph to represent the tree of the end item, transforms it in a matrix (matric capture amount of component and lead time), and makes Laplace transforms to describe the timing relations and develop the MRP equations (Grubbstrom, 2007).

Others researchers extend the research into other areas of the supply chain. Kovačić & Bogataj (2010) extend the theory to reverse logistics of assembly systems.

Grubbström, Bogataj & Bogataj (2010) work with optimization of lot sizing using the theory. But there is a long path to describe the MRP environment in mathematical terms as extensions of stochastic demand (including backlogging), capacity limitations, and non-assembly systems.

b. Characteristics of MRP

One of the important characteristics of MRP is explosion. It is the process that permits the "calculation of gross requirements for the components at the next level down the product structure" (Baker, 1993, p. 573). The end item can be "n" level of explosion. Gross to net explosion is a key element of MRP systems. This communication among the levels permits calculation of the needed quantity in each level. One level depends on the other level; this means that one demand depends on the demands of the other levels, and is thus a dependent demand. In the end, this process calculates how many of each subassemblies and components are needed to produce an end product (Vollmann et al., 2005).

Explosion tells us the quantity that needs to be produced or purchased, and the lead time says when it has to occur. Lead time refers to how long it takes for a product to be produced, assembled, or purchased. Based on this information, the order has to be placed. In traditional MRP, the lead time is a factor to calculate the order (Silver et al., 1998; Vollmann et al., 2005).

MRP has a function to indicate the production need. MRP indicates the needed machine or labor hours and can work with capacity analysis before the MRP calculation or after. Rough cut capacity planning (RCCP) calculates the capacity before. With information about availability of resources and the product required, the RCCP function calculates the availability of resources in the period. The advantage of RCCP is that it has few data requirements (Baker, 1993, pp. 577–578). Capacity requirement planning (CRP) is processed after the MRP calculations. It is more detailed, has more information, and requires more data. CRP shows that the order can violate capacity.

Many MRP systems contain RCCP and CRP modules, but these functions do not make decisions. They are only tools for the managers who make decisions. The RCCP

shows obvious capacity problems where the managers can see unrealistic planning. CRP shows the problems in more detail, such as the labor capacity in a week. These tools do not fix the capacity problem; the manager has to change the MRP calculation to make the planning feasible (Baker, 1993; Silver et al., 1998).

c. MRP Working

If the information that MRP uses to process and calculate the orders changes, then the managers have to regenerate the calculation. The process of regeneration demands intensive use of the system. Many times, the managers have to decide the frequency and period for which the MRP must be regenerated. There are techniques that help in this issue as net change approach. This technique regenerates specific tree product, or regenerate items that have updates in the system. But the managers have to take care with the number of processes being tracked because many times the manager cannot understand all the changes involved and can cause instability in MRP management.

Managers have to decide about the time frame that they use to manage the MRP. When they opt for a short time frame, the planning is more accurate but computational processing increases significantly, so the managers have to balance the frequency of regeneration against the workload involved (Baker, 1993, pp. 574–575; Vollmann et al., 2005, p. 236).

Another question about MRP is lot sizing. MRP calculation was developed to work with a "lot-for-lot" (LFL) concept. This lot sizing procedure calculates the batch quantities that will be purchased or produced in order to meet net requirements. The problem of lot-for-lot is that it does not consider any of the economic trade-offs or physical factors.

The MRP model presupposes a deterministic view that many times does not have safety stock. In uncertain situations, however, the safety stock and safety time can be used to avoid the loss (Baker, 1993, p. 582). Safety stock is used to cover the uncertainty of demand. According to Vollmann et al., "Safety stock is a buffer of stock above and beyond that needed to satisfy the gross requirements" (Vollmann et al., 2005, p. 237).

Safety lead time covers the uncertainty with the suppliers; to decrease delivery uncertainty, an order is made before it is actually needed to match the gross requirement (Vollmann et al., 2005, p. 237).

d. MRP Weaknesses and Optimizations

Two main points of MRP are lot size and buffers to use in the model. This section discusses many methods of lot size and buffers showing the challenge and use in different situations.

(1) Lot Sizing

MRP systems were designed as deterministic models. Lot-for-Lot that has been used but this procedure does not support the best inventory cost. Also, many MRP systems do not support lot-sizing rules other than EOQ and LFL. This characteristics can cause higher inventory costs (Silver et al., 1998, p. 618).

To decrease this problem, several approaches were developed to choose the best lot size in different situations (Gaither, 1983). This research presents the primary approaches and the concepts to discuss their use.

- **Wagner and Whitin Model (WW)**: Wagner and Whitin (1958) developed an algorithm that uses dynamic programming to minimize cost. This algorithm is used as reference to compare with other models because the solution is robust. The problem is that this module uses a lot of computational resources. Another reason is that the best solution has the property that alterations in the requirements scheduled for a later period may cause changes in the lot size in the early period and cause nervousness in MRP (Baker, 1993, pp. 587–588). Many recent studies try to test this model. Vargas (2009) used the WW algorithm for determining the optimal solution when demand is stochastic and non-stationary. Ali et al. (2013) used it to determine lot sizes, replenishment cycles, and schedules. They propose a logistics-based approach to a class of inventory problems with shortage and time-decay functions (Ali et al., 2013). Fleischhacker and Zhao (2011) generalize the WW model to incorporate the risk of failure. They showed that a stochastic model, referred to as the failure-risk model, is equivalent to the deterministic WW model if one adjusts the cost parameters properly to reflect failure and destruction costs.

- **Economic Order Quantity (EOQ) Method**: this method makes it is easy to calculate order quantities but the great disadvantage is that the order quantities do not match requirements for a whole number of periods, thus producing residual inventories (Baker, 1993, p. 588; Silver et al., 1998, pp. 203–204).
- **Periodic Order Quantities (POQ) Method**: this module reduces the high inventory carrying costs associated with fixed lot sizes. The formula uses fixed order quantities based on an average demand rate in the EOQ equation (Baker, 1993, pp. 588–589; Silver et al., 1998, p. 214).
- **Part Period Balancing (PPB) or Least total cost (LTC) Method**: this procedure tries to equate the total cost of placing orders and carrying inventory (Silver et al., 1998, pp. 215–216).
- **Silver-Meal Heuristic or Last Period Cost (LPC)**: Silver and Meal (1973) developed this procedure that "selects the replenishment quantity in order to replicate a property that the basic economic order quantity possesses when the demand rate is constant with time" (Silver et al., 1998, p. 210).

There are other methods, including least unit cost (LUC), incremental order quantity (IOQ), marginal cost difference (MCD), and modified Gaither model. Those methods seek to find the best solution for the inventory costs in different situations. Readers who want to know more about the methods can read the following sources: Baker, 1993; Freeland & Colley Jr., 1982; Gaither, 1983; Groff, 1979; Silver & Meal, 1973.

With the proliferation of these methods, other studies sought to analyze and compare the methods. Gaither (1983) affirms that modified Gaither, Groff, and Silver-Meal models were demonstrated to outperform order models in terms of ordering and carrying costs. Millen and Blackburn (1985) developed an extended study to compare the single-stage lot-sizing performance. They sought to "structure the lot-sizing performance by isolating conditions under which certain lot-sizing heuristics dominate others." They found that no single method dominated under all conditions. Groff and Silver-Meal, however, tend to outperform the others.

Silver et al. (1998) did an experiment with lot sizing for individual items with time-varying demand. They added the silver-meal heuristic (SM) that has similar results to the Wagner-Whitin algorithm to compare the cost with the other models. They

concluded that SM and WW have better cost than the other models (Silver et al., 1998) with deterministic demand. Gaither (1983) conducted another experiment that included the Gaither model. The experiment showed the performance of the models that can be used as guidelines for MRP systems.

Wemmerlov and Whybark (1984) show different approaches to choose lot size using MRP, and compare a number of alternatives such as economic order quantities (EOQ), periodic order quantities (POQ), part period balancing (PPB), and the Wagner-Within algorithm. Wemmerlov and Whybark (1984) demonstrated with no uncertainty that the best result was achieved with WW, but with great computational cost. Under demand uncertainty, the inventory cost is 0.19 percent higher with EOQ than with WW, and PPB is 0.67 percent lower than the WW model. Therefore, all three models can produce good solutions. Under uncertainty, the inventory cost has no difference; the "EOQ rule carries with it its own safety stock" (Wemmerlov & Whybark, 1984, p. 16).

Fildes and Kingsman (2011) support the aforementioned result with a study about demand uncertainty and forecast error. The result showed that the cost with demand uncertainty is very different from deterministic demand. They found that EOQ is the best choice for the random noise process, though sometimes least total cost (LTC) can perform better. They observe that many studies are dominated by a research paradigm that emphasizes mathematics, and they think that information sharing in the supply chain is valuable. They conclude with the observation that "more empirical modeling that includes forecast error and less reliance on spurious mathematical simplicity is required" (Fildes & Kingsman, 2011).

(2) Buffering

A standard MRP system does not predict uncertainty in the calculation. Uncertainty demand, lead time, and production time are great sources of uncertainty that must be avoided. Many studies attempt to find a mechanism to calculate the best buffers to minimize the uncertainty.

Whybark and Williams (1976) studied the use of safety stock and safety lead time in MRP in response to four types of uncertainty: demand timing and quantity, and supply

timing and quantity. In demand timing, the gross requirement of the timing changes from period to period. Supply timing is related when the order from the supplier is not received during the lead time; then there is a variation on demand and lead-time timing. Demand and supply quantity are related to the variation of material to delivery based on planning (Whybark & Williams, 1976).

To minimize these uncertainties, there are buffer mechanisms. There are two ways to minimize this problem. One of the solutions is quantity safety stock, and the other is safety lead time. Quantity safety stock is similar to the calculus with the other inventory control models. Safety lead time consists of the orders arriving earlier than required in the planning (Vollmann et al., 2005, pp. 484–489; Whybark & Williams, 1976).

Whybark and Williams (1976) started the first study to understand both buffers. They developed a simulation that represents the MRP system to test the two buffers with different coefficients of variation and uncertainty. The result showed that safety lead time has better results with timing uncertainty. For quantity uncertainty, safety stock had better results. The simulation indicates a high uncertainty, and so it is very important to choose the right safety method.

Another buffer concept is called the hedging buffer, which tries to protect finished goods against uncertainty. The buffers do not need to be maintained in the form of end-items; the idea is to build up buffer points in the stages of the product structure to decrease uncertainty (Wijngaard & Wortmann, 1985). Finished goods have to be controlled by MPS managers, components by material coordination, and work in process (WIP) levels by SFC control. This kind of buffer can be considered important because safety stock could be deployed selectively; it is easily incorporated within the MRP system (Baker, 1993).

Molinder (1997) examined how uncertainty in lead time and demand affect safety stock and safety lead time. He supports the finds by Whybark and Williams (1976) and contends that high levels of lead time and demand variability have a strong effect on the level of the optimal safety stock and lead time.

4. Use of ERP in Maintenance

Some studies have attempted to use MRP in the maintenance supply chain. Ghobbar and Friend (2007) surveyed 176 maintenance companies (104 airline operators and 72 maintenance service organizations) to find how they determined reorder point systems for their parts and components for operation and maintenance. They found that 66 percent of the maintenance organizations and 57 percent of airline operator organizations "were aware of MRP but had neither used nor investigated it further" (Ghobbar & Friend). These results showed 83 percent of the companies use ROP model, and more than 50 percent of these companies were not satisfied with their inventory management system (Ghobbar & Friend, 1996).

Newman (1985) argued that MRP could be used for preventive maintenance requirement planning where its use could have multiple benefits: part consumption could be tracked and maintenance personnel could be better used. His model showed some promise for integrating the maintenance schedule with supply chain management.

Molinder (1997) studied how an MRP system was affected by stochastic demand and lead times. He used a "simulation with the objective of analyzing the effects of different sources of uncertainty in MRP systems" (Molinder) He found that high variability had a strong effect on the level of safety stock and safety lead time required. An adaptation of MRP to maintenance had predicted this uncertainty.

Bojanowski (1984) developed a variant of MRP, service requirement planning (SRP), to prioritize routine mechanical inspection and machine maintenance sequences. Ettkin and Jahnig (1986) presented a framework for adapting MRP II to maintenance functions for waste reduction. They thought that this model could be used successfully in maintenance management because of the similarities between the manufacturing and maintenance processes.

Another potential point of confusion centers on remanufacture and maintenance. The concepts and their management are different. Ptak and Smith state, "[The] remanufacture process is an industrial process in which worn-out products are restored to like-new condition" (Ptak & Smith, 2011, p. 295). Remanufacturing disassembles and

recovers the equipment. Ferrer and Whybark note, “It requires the repair or replacement of worn out or obsolete components and modules” (Ferrer & Whybark, 2001a, p. 87). Generally, inoperable units are disassembled, cleaned, repaired, and placed in inventory to assemble a new unit. On the other hand, “maintenance constitutes a series of actions necessary to restore or retain an item in an effective operating state” (Blanchard et al., 1995, p. 1). Maintenance management links scheduled and unscheduled maintenance to maintain the availability of equipment. Remanufacturing can be a type of maintenance.

There are studies comparing MRP to remanufactured industries, Deput et al. (2007) propose a new MRP that calculates the number of units produced each period and the number of components needed to assemble the product. Ferrer and Whybark (2001b) present the “first fully integrated material planning system to facilitate the management of a remanufacturing facility.” Other research seeks to find the optimal number of used products, or “cores,” to procure and disassemble, and the optimal quantities of new parts to procure (Gaudette, 2003).

Many studies apply MRP with environmental uncertainty, many examples of MRP’s use in a variety of industry sectors, and new MRP use in the remanufacturing sector; however, there are few studies of MRP’s use in the maintenance sector; a few models only mention the possibility. Ernst and Cohen (1993) explain “Companies that apply ERP software without customizing the need of this environment have bad experience and deliver poor service.” The majority of existing ERP does not have a capacity to manage the uncertainty in the maintenance environment because these ERP systems are customized to the manufacturing sector.

This research fills this gap and presents a model that connects the elements of the maintenance supply chain. It will analyze the elements of the maintenance supply chain with a focus on general systems theory and information processing theory. Therefore, it is necessary to define these theories.

D. GENERAL SYSTEM THEORY

To address the research problem, general system theory is used. The following discussion provides the theory concepts, the use the theory in supply chain, and how the theory can relate with the problem.

1. Identifying the Theory

In the construction of a theoretical perspective for studying information integration among the elements of the maintenance supply chain, general systems theory (GST) provides a useful view to understand these relations. Systems theory tries to provide a framework that models complex interactions about the phenomena in the world. This theory encourages the development of a "global, more unitary consciousness, team work, collaboration, learning for life, and exposure to the universal storehouse of accumulated knowledge and wisdom" (Laszlo & Krippner, 1998, p. 12). A truly integrated supply chain does more than reduce cost; it creates value for the company and for that company's partners as well (Lee, So, & Tang, 2000; Zhao, Zhao, & Hou, 2006). The use of this theory to integrate the information in the maintenance supply chain provides an excellent framework for this research.

This theory claims that the components cannot be reduced to their constituent parts because the relations are destroyed when the system is divided. The properties of the parts can be understood only in the context of the larger whole. In quantum physics, the subatomic particles have no meaning as isolated entities but can be understood only when their interconnections and relations are linked (Capra, 1996). So, the properties of the elements are lost when the components are removed from the whole or the whole is broken down to its components (Laszlo & Krippner, 1998, p. 10).

The famous researcher and biologist Ludwig Von Bertalanffy wrote that General Systems Theory "is a general science of wholeness" (Bertalanffy, 1969, p. 37). Guberman (2004), however, criticizes this view, thinking that Bertalanffy fails to create the mathematical science of wholeness. As a biologist, he formulated that living organisms perceive things in integrated patterns, as meaningful organized wholes (Capra,

1996). Capra states, “Living systems are open systems that maintain themselves far from equilibrium in this steady state characterized by continual flow and change” (Capra, 1996).

The cybernetics community continued the research from the second half of the 20th century. They developed the concepts of the feedback loop and networks (Capra, 1996). Rosenblueth et al. (1943) defined feedback as a mechanism that organisms use to maintain a state of dynamic balance. They introduced the concept of circular causality, as well as self-balancing and self-reinforcing feedback loops. One important aspect of the feedback loop concept was to recognize patterns of organization; cybernetics community could distinguish the pattern of organization of a system from its physical structure (Capra, 1996). Sterman (2000) argues that all dynamic situations arise from the interaction of two types of feedback loops: positive or self-reinforcing loops and negative or self-balancing loops. Positive loops tend to amplify what happens in a situation. Negative loops oppose change.

Capra (1996) affirms that “self-organization is the spontaneous emergence of new structures and new forms of behavior in open systems far from equilibrium, characterized by internal feedback loops and described mathematically by nonlinear equations.” In this way, “every dynamic system generates its own form of intelligent life” (Ashby, 1947). If each system is connected, then life is a big dynamic system network.

To propagate the information and interrelationships, the concept of a network was developed. Each object in the system is considered a network of relationships. The entire material universe is seen as a dynamic web of interrelated events. Knowledge is considered a network that transmits to others. As Barabási (2003) affirms, everything is connected with only a few degrees of separation. This concept makes it hard to represent models of the universe. Systems theory attempts to construct a representation of a small portion to explain a phenomenon. It is very difficult to represent a complete and definitive understanding of a phenomenon; therefore, sciences always seek to “approximate descriptions of reality” (Capra, 1996).

With the development of system dynamics, computers can initiate studies in artificial intelligence. This set of tools encourages and simulates the study of the complexity of a system (Simon, 1996, pp. 172–173). System dynamics is "grounded in the theory of nonlinear dynamics, a feedback control developed in mathematics, physics, and engineering" (Sterman, 2000, p. 5).

The study of dynamic environments brings new ideas and theories, such as catastrophe, chaos, genetic algorithms, and cellular automata. Catastrophe theory brings a solid body of mathematics to a dynamic environment. In this environment, the system can be stable, but a stimulus can upset the system and cause variables to increase without limit. For chaos theory, small perturbations cause large changes in a path. All the complexity of the world can be represented in sophisticated algorithms and simulations (Simon, 1996, pp. 170–180). Computers can be used to learn, create, and interpret symbols based on a set of rules of information processing to represent these systems (Capra, 1996).

GST claims that the properties of parts and their interactions can represent the whole system. But in the real world, systems have many subsystems. Simon discusses a hierarchic system where the system is composed of interrelated subsystems and each "subsystem is subordinated by an authority relation to the system it belongs to" (Simon, 1996, p. 185). If the subsystem is broken down to its component parts, the end parts cannot be explained in isolation; the system is an assembly of small and distinct parts. The system design seeks to "understand a situation as a system of interconnected, interdependent, and interacting problems." System design focuses "on finding solutions and creating things and systems of value that do not yet exist" (Laszlo & Krippner, 1998, pp. 20–21).

2. The Use of Theory in the Supply Chain

The supply chain "is a goal-oriented network of processes and stock points used to deliver goods and services to customers" (Hopp, 2011, pp. 6–7). It can be seen as a large system that connects with other subsystems. Many authors try to use systems theories to explain phenomena in the supply chain.

Zhao explained that GST is a meta-theory that can be used in many contexts (e.g., biology, physics, supply chain) to describe general relationships of the empirical world. For Zhao, GST "can be used to integrate existing theories or invent new theories to fit the needs of different situations" (Zhao et al., 2006).

Janvier-James (2012) related the supply chain to GST. He explained that a supply chain model has not been achieved but that systems theory can help bring it about. The supply chain can be explained as a system that has a boundary that divides a system from its environment. A supply chain is a manmade system that has many subsystems that interact among themselves. With new technology and technological evolution, the supply chain changes and adapts with time. Janvier-James used Yourdon (1989) to postulate some principles that can be used in the supply chain; these include "the larger the system, the more resources are necessitated to support the system," and "the more complex a system is the less compatible it is to changing environments." These concepts helped to explain the difficulty in managing a supply chain.

Although a supply chain is a manmade system, it is a complex, adaptive system that is designed to improve competiveness and reduce operating costs. The supply chain is forced to adopt different modes of supply chain structure in different competitive environments to work as a self-adaptive system (Shaoyan, 2009; Shi et al., 2009; Zhang et al., 2007). Because of this, there are many supply chains that try to adapt and survive in each environment and situation.

The synergy among the supply chain elements can bring a competitive advantage to this environment. The degree of synergy will depend on how the elements of the supply chains are related. The information interaction among the elements of the supply chain can transform the elements in a whole system. When the elements of the supply chain are very closely tied, they will work as a system. The manner in which the information is exchanged is crucial in order for the supply chain to work as a system. Therefore, it is important to understand the sharing, integrating, and collaborating of information in the supply chain to understand it as a system.

This research uses the following definitions about sharing, integration, and collaboration. Sharing information is the first step of collaboration. Information sharing consists of sharing information among the elements of the supply chain in both forward and backward flows to provide adequate visibility within and across organizations to make decisions at many levels (Simatupang & Sridharan, 2002, p. 24). E-business architecture permits companies to share the information through standard protocols such as electronic data interchange (EDI) (Papazoglou, Ribbers, & Ribbers, 2006).

At the strategic level, sharing information can help managers to understand the competitive advantage of seeing the whole supply chain. On the tactical level, it helps the managers to mitigate uncertainty and makes planning more reliable (Simatupang & Sridharan, 2002, pp. 24–25). Without sharing information, some problems can happen as a bullwhip effect. Lee et al. (2004) defined the bullwhip effect as a phenomenon that has large variance, orders of magnitude, and amplified effect of stock. Beer game example is a good example of bullwhip effect, readers can read Senge (2006) to understand better the bullwhip effect.

Information integration links the sharing of information within and across the organization by integrating their relationships, activities, functions, processes, and locations using information technology (Jitpaiboon, 2005). Internal information system integration "is the cooperation between business functions within the firm on an internally consistent set of strategic, operational, and infrastructural information systems practices using information systems." External refers to cooperation between a firm and its trading partners. Firms apply computer and information technology to support internal and external integration. Jitpaiboon explains, "The firm can only integrate with external partners through information technology when it is internally integrated and has an infrastructure in place" (Jitpaiboon, 2005).

Collaboration is the next step after sharing and integrating the information where the companies need a high degree of symbiosis. Collaboration systems have to demonstrate a collaborative culture in the managers, performance measurements, and

integrated policies to improve value in the chain. The collaboration involves creating a synergy where all organizations together are larger than the sum of each organization acting alone (Cao, 2007).

3. Relating the Theory to Variables

This research connects the information of the elements of the maintenance supply chain and studies the effects on inventory costs compared to a traditional model of inventory control. The experiment will analyze when the components of the system working in isolation and in integration. The elements of systems theory (e.g., feedback loops, self-organization) help to explain the causality that exists among the elements.

The following reasoning represents the motivating logic for using the systems thinking theory. The literature considers whether (1) the system has a feedback loop that can respond effectively to any change of failure rate or usage of the system; (2) the feedback information helps the organization self-organize and make better decisions; (3) with information synergy between the elements of supply chain, the whole system is transformed and is more efficient more than when it works alone; and (4) when the system components work in an isolated form and the properties of the system are broken. The literature then considers whether the result will be low inventory costs and more responsiveness to any external or internal change when the framework integrates all information in the maintenance supply chain.

If the elements are integrated, the elements of the supply chain work as a system, and inventory costs and response time have better performance. If elements work in isolation in the supply chain, then the system property is broken and there is a worse performance in the whole supply chain.

E. INFORMATION PROCESSING THEORY

Information processing theory provides significant elements to understand the problem. The following discussion provides the theory concepts, the use the theory in supply chain, and how the theory can relate with the problem.

1. Identifying the Theory

March and Simon (1993) proposed the first approach toward an information processing view. They argue that "success [in an] organization is linked with the ability to process and communicate the information required to carry out and coordinate its work processes" (Levitt, 2007; March & Simon, 1993). Galbraith (1974) and Tushman and Nadler (1978) consolidate the information processing theory. Galbraith relates the organization structure to the need to process information. Tushman and Nadler present a model that seeks to structure the organization based on uncertainty and information processing. Finally, Levitt et al. (1999) experiment on a "quantified, extended and validated information processing theory."

In the environment of this research, the information about each component failure is not available and maintenance information could not be integrated with supply subunits. Often, inventory control has to use historic information to predict the purchasing of material, and the supplier generally does not integrate planning information with the client need. This entire gap causes a high level of uncertainty in the maintenance supply chain environment. Galbraith (1977) defines "uncertainty as the difference between the amount of information necessary to perform a task and the information already possessed by the company." This research focuses on analyzing this environment with information processing theory.

Moreover, Galbraith (1974) analyzes the relation between uncertainty and information to formulate the information processing theory. Information processing relates "to the gathering, interpreting, and synthesis of information in the context of organization decision making" (Tushman & Nadler, 1978). His theory claims that "the greater the task uncertainty, the greater the amount of information that must be processed among decision makers during task execution in order to achieve a given level of performance" (Galbraith, 1974). He argues that there are two organization strategies to coordinate the uncertainty: 1) reduce the need for information processing; and 2) increase the capacity to process information.

Using slack resources, which minimizes the amount of interdependence between subunits and decreases the problem of overload in the hierarchy chain, can reduce the need for information. One of ways to accomplish this in the supply chain is to increase the buffer in the inventory; that is, increase the safety stock. This has a cost, however. The other way is to create self-contained tasks to reduce the amount of information processed. This strategy shifts the basis of the authority structure from one based on input, resource, skill, or occupational categories to one based on output or geographical categories. The problem is when the resources are divided, other departments lose resource specialization (Galbraith, 1974).

Galbraith explains two additional ways to increase the capacity to process information. The first is to create a mechanism that increases the indicators of decision making; this means an increase in vertical information systems. In this way, companies can collect data on many levels and process the information to make decisions. Mechanisms such as the Balanced Score Card are good examples of employing this strategy (Galbraith, 1974).

Another proposed strategy is the creation of lateral relationships. This stratagem "move[s] the level of decision making down to where the information exists." He proposes a physical mechanism of coordination such as direct contact, liaison roles, task forces, teams, and others. He argues that the greater the "uncertainty the lower [the] decision-making and the integration is maintained by lateral relations" (Galbraith, 1974). Galbraith concludes that the organization form is related to uncertainty.

Furthermore, Tushan and Nadler (1978) propose that the organizations have to develop mechanisms capable of dealing with uncertainty. Organizations have to identify critical information processing needs to create the subunits to manage that information. All these subunits have to link with coordination and control mechanisms; generally, the more complex the mechanisms of control and planning, the greater the "ability to process information and deal with inter-unit uncertainty" (Tushman & Nadler, 1978).

For them, the processing information has to be weighted, and high capacity has to be used only where the organization requires a great deal of processing and vice-versa.

According to Tushman and Nadler (1978), "The information processing approach suggests that the organization must adapt to varying information processing demands." Organizations have to identify critical information processing needs to create the subunits to manage that information. All these subunits have to be linked with coordination and control mechanisms.

For information processing theory, "organizations are seen as a collective decision making system in which the processing information serves as the primary focus of activities" (Leweling, 2007). In one of the latest updates to information process theory, Galbraith (2012) explains that vertical information has been enhanced by multi-dimensional planning (e.g., inventory and maintenance manager together—two-in-a-box structures), and lateral relations focus on collaboration information (collaborative software) and collaborative managers. This means that the information and decisions are more integrated.

2. The Use of the Theory in the Supply Chain

In the supply chain, information processing theory is used to explain the relation among the organizations. There are studies on the application of the theory to propose structural modification in organizations with vertical analysis and horizontal information systems to increase the information process (Bolon, 1998). Swanson applied the information-processing model to analyze maintenance management (Swanson, 2003). She found that maintenance organizations respond to environmental complexity with the use of computerized maintenance management systems, preventive and predictive maintenance systems, coordination, and increased workforce.

Other research presents a new perception of information sharing within supply chains based on organizational information processing theory. Posey and Bari propose a conceptual model that shows that if information within and across supply chains is more compatible, it can increase information-processing capabilities (Posey & Bari, 2009). Flynn and Flynn explain that some firms found alternatives to processing information by using "management-intensive solutions, rather than technology-intensive solutions" (Flynn & Flynn, 1999, p. 1044).

In relations among organizations, Walter (2005) found that if companies add structure to the decision-making process it enables them “to reap the full benefits of strategies alliance.” These companies can increase performance if they agree that they need to communicate to reduce uncertainty. If one company does not see the importance of reducing uncertainty by increasing communication, the supply chain cannot be effective (Oosterhuis, van der Vaart, & Molleman, 2011).

Other studies show that interaction between the supply chain effects of information needs and capability has a significant effect on performance (Premkumar, Ramamurthy, & Saunders, 2005). One of ways to build and increase integration and collaboration is cloud computing technologies. Cegielski et al. (2012) found that information processing requirements and information processing capabilities affect the intention to adopt cloud computing in a supply chain. Gattiker showed that if interaction among marketing and manufacturing increases, the ERP of the companies will have better performance. All of these studies used information processing theory to show that integrating and processing information is vital in the supply chain environment. “Organic Theory implies that ERP systems should be detrimental in dynamic environments while Information Processing Theory suggests that they should be advantageous.” The experiment found that information processing theory is right because information integration can decrease the level of uncertainty (Tenhiälä & Helkiö, 2012).

Levitt’s ongoing research uses a simulation virtual design team (VDT) to “design project organizations as engineers design bridges,” and predict and evaluate the performance of an organization. The research extends Galbraith’s theory that focuses on organizational behavior at the level of the organization, and does not concern itself with the internal dynamics of the organization. Levitt’s experiments extend information processing theory to a micro-contingency model of organizational behavior (Levitt et al., 1999; Thomsen et al., 2005). Leavitt et al. note, “the experiment models the effects of task and organizational variables on low-level behaviors of individual team members, and then simulates behaviors and interactions among team members to generate aggregate project outcome predictions from the bottom-up” (Levitt et al., 1999). Their last experiment tries to simulate a military environment of command and control (C2) (Levitt

et al., 2010). The VDT passed through many evolutions, such as VDT-1, VDT-2, VDT-3, and VDT-4. For more details about the research, the reader can refer to Levitt (2007, 2012).

The researches that were done on the supply chain focus more on surveys and group interviews. Levitt's experiment extends the theory to micro-organizations, while Galbraith covers the organization as an element. No study of integration among the elements of the supply chain shows the implication of connecting lateral and vertical information to decrease uncertainty. This research addresses that gap to extend the use of information processing theory to supply chain elements.

3. Relating the Theory to Variables

This research will analyze information processing theory, focusing on two approaches. The first is a reduction in the need for information processing; this approach uses the most common model for inventory control: economic order quantity (EOQ) with the reorder point (ROP) model. The second approach is to increase the capacity to process information. This line uses a new model that connects the information in the supply chain; it is called maintenance enterprise resource planning (MERP).

The maintenance supply chain is an environment with high uncertainty where there is a need to process a large quantity of information. In this environment, if one organization processes information but another is not connected to the first organization or does not process the information, the whole supply chain can be affected. Different response times between the supply chain elements can affect the whole supply chain.

The two approaches are linked by the ability of the organization to coordinate and process the information. If a company cannot integrate department information, if the non-routine tasks are more frequent than the capacity of the company to process the information, and if technology cannot increase the company's information processing, then the company uses strategies to reduce the processing of information. Thus, a model such as EOQ, which uses basic information to make decisions, is employed to support the organization and to create buffers to decrease the level of uncertainty in maintenance management.

Furthermore, (1) if the company can integrate lateral and vertical information within and across organizations; (2) if the company can decrease the processing time to make decisions; and (3) if the company can integrate the elements of the supply chain, then the new MERP model can increase the capacity to process information and decrease the uncertainty in this environment. This, in turn, will result in lower inventory costs and more responsiveness to any external or internal change. Figure 7 presents the Galbraith theory with the supply chain model of research.

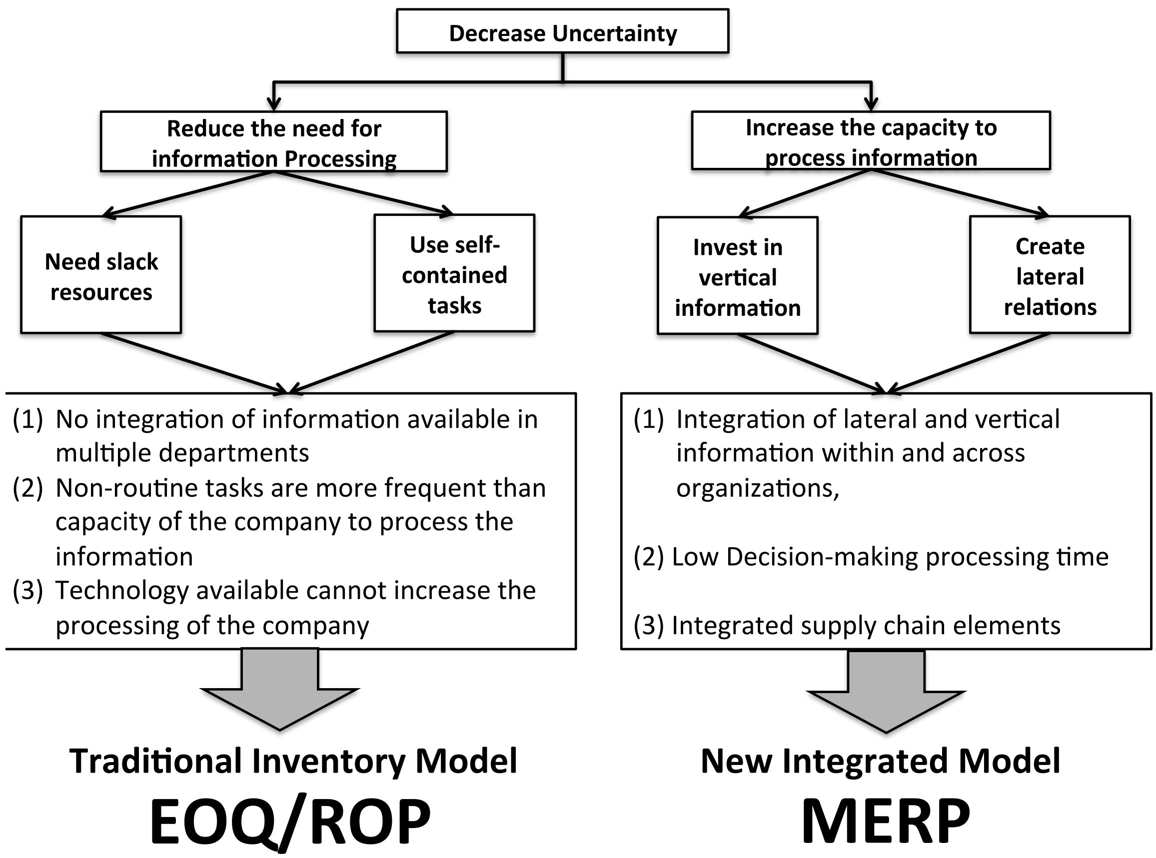

Figure 7. Galbraith strategies with supply chain models.

The aforementioned information sets the stage for the main hypotheses of the research. In the maintenance supply chain, if information is integrated the supply chain can process more information and decrease the level of uncertainty and the inventory costs related to maintenance management, such that the new model can respond more

effectively to all changes in this environment. Now it is necessary to build and explain the new model: the maintenance enterprise resource planning (MERP).

III. MAINTENANCE ENTERPRISE RESOURCE PLANNING

The traditional inventory control system works with the assumption that every item is independently in demand, meaning that the demand for an item is independent of other items. Traditional inventory control for this model is accomplished by the EOQ model, production order quantity cost, and quantity discount model (Heizer & Render, 2007, pp. 489–490).

A. INDEPENDENT AND DEPENDENT DEMAND

Traditional MRP works with the assumption that there are independent demand items and dependent demand items. Independent demand items are end-product items in a manufacturing process, such as an aircraft or engine (Vollmann et al., 2005, p. 134). Dependent demand means that the demand for one item is related to the demand for another item. Following the aircraft example, the items to assemble the aircraft, such as spare parts, are dependent demand items. An engine that is used in the assembly of an aircraft is a dependent demand item in relation to the aircraft, but the engine can be an independent demand item to the manufacturer (Heizer & Render, 2007, pp. 562–563).

The maintenance enterprise resource planning, MERP, model uses the principle that maintenance is an independent demand. For example, the scheduled and unscheduled maintenance that is performed on aircraft, engines, generators, and landing gear are considered independents events. Dependent demand items are the spare parts that are used to perform the maintenance.

B. THEORETICAL APPROACH OF MERP

According to March and Simon, "organizations are seen as sophisticated information-processing and decision-making machines" (March & Simon, 1993). The maintenance supply chain, therefore, is an information flow that has to be connected, integrated, and processed to reduce the uncertainty and, following system theory, work as

a system. The proposed model seeks to deliver a model that matches required need to a maintenance supply chain and reduces uncertainty by integrating information and elements in the supply chain.

Many inventory models, such as EOQ, seek to replace material based on simple mathematical models. This is unrealistic, however, because of the dynamic environment in the maintenance supply chain (Ptak & Smith, 2011). MERP seeks to connect the dynamic information source(s) based on systems theory and information processing theory. The proposed model seeks to connect the causal problem with the effect through the elements of the supply chain by integrating information. This process consists of the following elements: user, system, depot, warehouse, and suppliers.

When a user uses the equipment/system—an aircraft in our example—after a period, the system can require maintenance. To do maintenance in a shop depot, material and human resources are required. The warehouse supplies the required material to the depot and/or orders the requisite material from the suppliers. The warehouse has to have the stock on hand to meet the uncertainty of client need and supplier process. When material is available, suppliers deliver material to the warehouse. The depot does the maintenance and delivers the serviced equipment to the user.

MERP seeks to integrate information from each of these elements of the supply chain, as well as the elements themselves. As system theory affirms, if an element is disconnected, the properties of the system are broken (Capra, 1996; Laszlo & Krippner, 1998). The MERP model ensures that the information of each element is connected, recorded, and processed so that each element can react quickly in a dynamic situation. MERP functions to reduce uncertainty, and consequently, the elements of the supply chain can work as a system. Figure 8. presents the basic maintenance supply chain process.

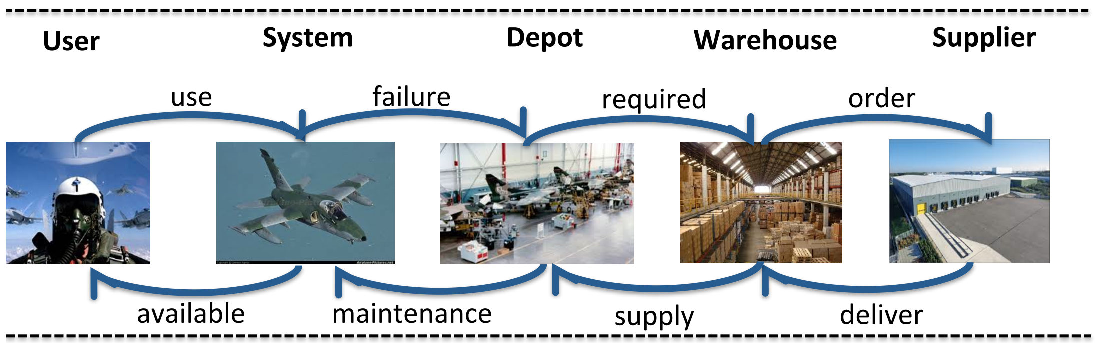

Figure 8. Maintenance flow.

To reduce uncertainty, Galbraith (1974) proposed two approaches: create lateral relationships and invest in vertical information. This model connects the lateral and vertical elements within and across the organization.

External to the organization, MERP has to connect the information of the clients and suppliers. For the users, MERP needs to know the failures, maintenance tasks as well usage of equipment forecast. For suppliers must send information about production and delivery, creating lateral relationships.

The client and supplier information is integrated with information owned by the elements inside of the organization. Using external information, the model connects the information about what has been purchased, transported, stocked, and maintained. All lateral information needs to be coordinated and processed. The equipment information also needs to be recorded so that other functions can use it. Planning and control functions are responsible for these tasks. These functions improve vertical information available to the managers who make the decisions. The vertical and lateral integration of supply chain elements providing information are presented in Figure 9.

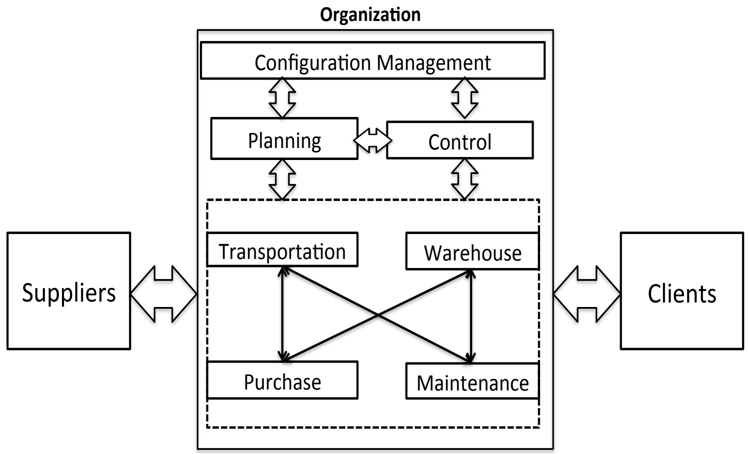

Figure 9. Lateral and vertical integration.

The MERP model connects the elements of the maintenance supply chain—laterally and vertically—and decreases the degree of separation among the elements of the supply chain, enabling these elements to work like an integrated system. When these elements are connected, a new network is formed. These environments will permit availability of information, decreasing delay and uncertainty, and increasing timely response.

C. MERP AND MRP COMPARISON

MERP is customized to integrate the information in the maintenance supply chain. Traditional MRP II uses information about the client to predict manufacturing. MERP uses the information about the equipment failure to predict future maintenance. To connect the elements of the supply chain, each model takes different types of information and makes different types of decisions. Table 6 presents the similarities and differences between MERP and traditional MRP II systems.

Table 6. Correspondence between MRP II and MERP modules.

Traditional MRP II	MERP
SOP—Sales and operation planning	MOP—Maintenance and operation planning
MPS—Master production schedule	MMPS—Maintenance master planning schedule
MRP—Material requirement planning	MMRP—Maintenance material requirement planning
BOM—Bill of material	CONSYS—Configuration management system

Sales and operation planning use information about consumption, as well as sales, to predict long periods of manufacturing. Maintenance operation planning uses information about failure rates and equipment use to predict the maintenance for long periods. The master planning schedule is used to detail the manufacturing process. The maintenance master planning schedule (MMPS) is used to schedule the corrective and preventive maintenance based in the time frame and capacity that organization uses.

MRP enables managers to plan the quantity of purchases and shop orders based on the inventory information and the bill of material. On the other hand, MMRP enable managers to plan for the shop orders and purchase orders based on inventory and maintenance data. The configuration management system supplies information that is used in the preventive and corrective maintenance.

D. MERP INTEGRATION AND OPERATION

MERP is a planning and control system used to integrate lateral information and increase vertical information availability to reduce uncertainty in the maintenance supply chain. MERP has many modules and systems that are responsible for integrating and processing the information within and across the organization. Figure 10 presents the model.

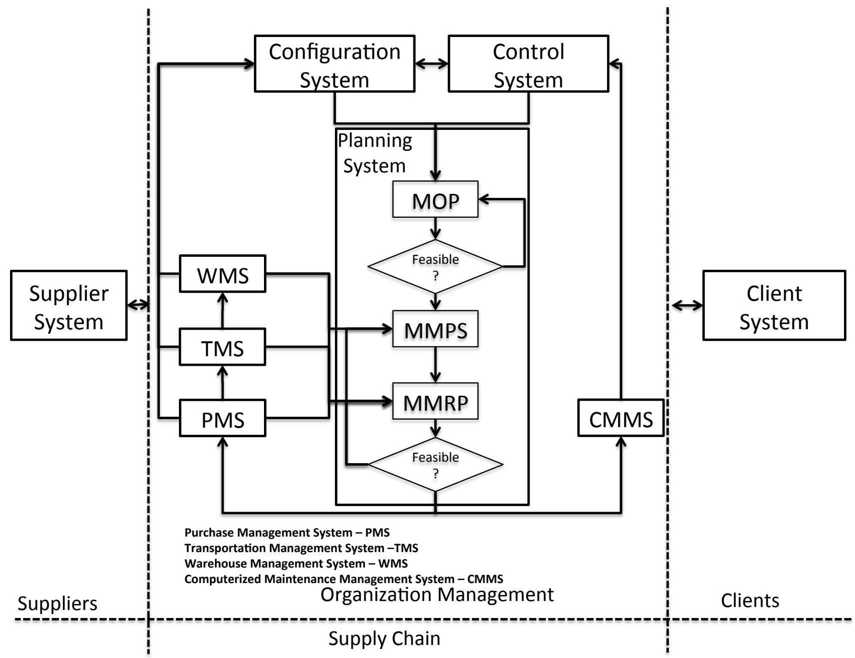

Figure 10. Maintenance enterprise resource planning—MERP.

One of most important functions in MERP is planning. The planning system has three components. The first component is maintenance and operation planning (MOP), which calculates a long-period corrective and preventive maintenance forecast based on client information (e.g., failure rates, equipment use). MOP calculates, per year, the quantity of maintenance and the budget need. This component uses information as failure rate, equipment usage forecast to predict the maintenance. If the quantity of maintenance projection is financially feasible, the information is transferred to MMPS; if not, a new scenario is recalculated.

If the scenario is approved, the MMPS calculates the maintenance quantity per period. To calculate, MMPS takes information about item quantity in stock and in the production line. Afterwards, this function calculates the work order quantity that has to be opened in a period. Then, the work order plan information is transferred to the MMRP.

In MERP, the bill of maintenance (i.e., the materials that are used in the maintenance) is dynamic. Every time, when maintenance uses a material, the bill of material is updated. Based on this information, MMRP calculates the need for new purchase by taking information on stock, acquisition, transportation, and lead time. If this

scenario is financially feasible, the information is transferred to the computerized maintenance management system (CMMS) and purchase management system (PMS); if not, a new scenario is recalculated.

Other systems that support MERP include the warehouse management system (WMS), which supplies information about the stock, the transportation management system (TMS), which supplies information about delivery item, and the PMS, which supplies information about the purchase process. CMMS supplies information about the end-of-work order.

Configuration and control systems are closely linked with information processing to reduce uncertainty. A configuration system is responsible for maintaining the information about an item's primary configuration and its real configuration, the item usage, its maintenance type, tasks, and needed material. The control system updates information in the configuration system and sends information to the other modules and systems.

There are two external functions. The supplier system interacts with the purchase and planning functions to attend to the organization's needs. The client system integrates the information on item usage and failure to plan the maintenance. All systems and components are used to produce a feedback mechanism that increases the capacity to process information to reduce uncertainty.

1. Components Description

The following sections described the main components of MERP, including the configuration and control systems, as well as the systems corresponding to the elements in the maintenance supply chain within the organization. Additionally, suppliers and clients who provide inputs/information to MERP are described. For these descriptions, the MERP is explained within the context of the maintenance supply chain for an aircraft.

a. Configuration System

The main tasks of this component are:

- **Basic Information**: this function is responsible for registering the initial information about the equipment and its components, such as part numbers, NATO stock number (NSN), unit of issue, and price.
- **Primary Configuration**: this function is responsible for registering the basic configuration of the repairable items of the aircraft. The aircraft can be composed of many repairable items. This function assembles the structure of the aircraft with quantity and position. Example: The airplane has two engines, two generators. One of these engines has two fuel pumps.
- **Maintenance Configuration**: this function permits registering of the maintenance type of the aircraft and its repairable components (e.g., preventive/predictive maintenance or corrective maintenance), the maintenance cycle, MTBUR, maintenance tasks, tools, man hours and materials that are needed to do maintenance.

Information shared:

- With information about maintenance performed in the organization and at the clients, the system updates the information about configuration and maintenance to send to the planning system (e.g., MTBUR, TBO, maintenance time, lot size, lead time, spare parts).

b. Control System

The main tasks of this component are:

- **Utilization control**: this function controls the use of the equipment and its repairable parts in the organization and clients. Also, this function compares the real use of the system with the use that was planned.
- **Reliability control**: based on failure and maintenance data and utilization of the item, this function calculates the mean time between failure (MTBF) and mean time between unscheduled replacements (MTBUR) of the repairable item. This function sends information to the maintenance configuration about the MTBUR of the item.

MTBUR is the probability of removing a repairable item and replacing it with some spare part during unscheduled maintenance in a given period and under specified operating conditions (B. S. Blanchard et al., 1995, p. 2, 112; Kececioglu, 1991, pp. 206–208).

$$MTBUR = \frac{1}{\lambda} \tag{3.1}$$

where λ is referred to as the remove and replace spare part in unscheduled rate.

- Maintenance control: this function controls maintenance cost, the maintenance due date, man hours used, and life cycle cost.

Information shared:

- This function sends information about MTBUR and use of equipment (e.g., update MTBUR, forecast use of equipment, amount of equipment in use).

c. Purchase Management System

The main tasks of this function are:

- This function controls and executes the purchases to the organization.

Information shared:

- This function receives the purchase planning information and updates the stages of the purchasing processes and delivery time. This function sends information to the planning system (MMPS and MMRP).

d. Transportation Management System

The main tasks of this function are:

- This function plans and controls the transportation of equipment and spare parts from clients and suppliers.
- Information shared:
- This function supplies information about transportation of the item. It supplies data to the planning system (MMPS and MMRP).

e. Warehouse Management System

The main tasks of this function are:

- This function controls the stock of the warehouses by receiving, picking, and shipping the material.

Information shared:

- This function controls the stock and gives information about the quantity of material in stock to the planning system (MOP, MMPS and MMRP).

f. Computerized Maintenance Management System

The main tasks of this function are:

- This function plans and controls the execution of maintenance tasks and updates the information about the material and man hours that are used in the maintenance configuration.

Information shared:

- This function receives the maintenance planning information and updates the maintenance tasks and delivery time. This function sends information to the configuration system and planning system (MMPS and MMRP algorithm).

g. Client System

This module connects information between the client and organization management. The communication can use electronic data interchange (EDI), machine-to-machine (M2M) techniques, or client-server architecture. The main tasks of this component are:

- **Item information**: this function is responsible to register the initial information about the equipment, such as the serial number of a part number, manufacture data, or lifetime.
- **Real configuration management**: this function is responsible for assembly of the actual configuration of the equipment. This function controls when an item is installed in or removed from the equipment.
- **Planning and control system**: this function is responsible for registering the utilization forecast of the aircraft by the client and controlling the use. If the client does not predict the use, the organization can use statistical methods to plan.
- **Computerized maintenance management system (CMMS)**: this function registers and controls maintenance that is done with the client, and updates the information about the materials and man hours that are used in the maintenance configuration.
- **Warehouse management system (WMS)**: WMS controls the stock of the client, if it is needed, and connects the information about the stock with the organization's management.

Information shared:

- This function shares information to the organization regarding use of equipment, real configuration of the system, failure data, and maintenance data.

h. Supplier System

This module connects information with suppliers. The communication can use electronic data interchange (EDI), machine-to-machine (M2M) procedure, or client-server architecture. The main tasks of this component are:

- The information about stock, purchase process, and transportation are shared and exchanged.
- The information about reliability, forecast, and use of the aircraft is shared with suppliers.

i. Planning System

The planning system is formed by three modules that connect and process information with the other systems and functions.

(1) Maintenance and Operation Planning

This module calculates the quantity of corrective maintenance (CM) and preventive maintenance (PM) over a long time period (two to five years). This module receives information about MTBUR, TBO, configuration, utilization forecast, and preventive and corrective maintenance costs, and calculates the quantity of maintenance in a period.

A generator of an aircraft is used to illustrate the maintenance forecast calculation. This scenario has 300 aircraft; the quantity per assembly (QPA) is two generators. The forecast is to fly an average of 75 hours per month for each aircraft by year y and y+1. The MTBUR rate is 5,000 hours, and the time between overhaul (TBO) is 3,000 hours. These parameters calculate an estimation of maintenance per year. The parameters are shown in the Table 7.

Table 7. Parameters to calculate the quantity of corrective and preventive maintenance.

Year	QPA	# of aircraft	Usage per month	MTBUR	TBO	Period
				5000	3000	
	x	y	h	λ=1/MTBUR	Z=1/TBO	t
y	2	300	75	0.001	0.0003	12
y+1	2	300	75	0.001	0.0003	12

To calculate the average quantity of maintenance, the parameters are multiplied. The formula is shown in Table 8. Calculation of quantity of preventive maintenance (PM), the parameters QPA, aircraft quantity, usage per month, TBO, and period are multiplied. For CM, instead to use TBO, it uses MTBUR and a service level (SL(K)) using Poisson distribution is used to increase the probability to find the item in the stock (Jones, 2006, pp. 12–13). The example in Table 8 uses k=90 percent, using the average 108 with SL=90 percent, which calculates as 121. The algorithm to calculate this number is provided in Appendix B.

Table 8. MOP—Quantity of corrective and preventive maintenance.

Average CM	Average PM	SL(k)	Qty CM	Qty PM
μ(cm) = x y h λ t	μ(pm) = x y h z t		Poisson.inverse(k, μ(CM))	
108	180	0.9	121	180
108	180	0.9	121	180

(2) Master Maintenance Planning Schedule

To calculate the quantity of maintenance that a maintenance depot has to do in a period-of-time, the model sums the quantity of CM and PM, the quantity of maintenance of a specific repairable item, and decreases the quantity of equipment that it has in stock and work orders.

To calculate the master maintenance planning, this module takes information from the configuration system about the average of maintenance time (MT) of PM and CM, lot size (LS) to do the maintenance (if applicable), and safety stock (SS) of the

repairable item. To illustrate the calculation, the maintenance time is one period; safety stock is 0, and lot size is 1.

The elements of MMPS are:

- Maintenance forecast (MF), based in MOP. It can be expressed in

$$MF(t) = \frac{(CM + PM)(t)}{(p)} \tag{3.2}$$

where t is a time frame of the period (this research uses "week" as the time frame) and p is the number of events in the period, in this case 52 weeks per year.

Example for t=1,

$$MF(1) = \frac{(121+180)}{52} = 5.79$$

- Ending order (EO)(t) is based on information at the end of the work order in shop, in a period t.
- Starting inventory (SI) is the quantity of the stock at the end of the period before:

$$SI(t) = EI(t-1) \tag{3.3}$$

Example for t=2:

$$SI(2) = EI(1) = 0$$

- Ending inventory (EI) is the quantity of equipment after processing the quantity that arrived and quantity that was used:

$$EI\ (t) = SI(t) + EO(t) + RO(t) - MF(t) \tag{3.4}$$

Example for t=3:

$$EI\ (3) = 0 + 0 + 5.79 - 5.79 = 0$$

- Receiving order (RO) is when the maintenance order will finish and is ready to use. It can be expressed:

$$RO(t) = (MF + SS)\ (t)\ -\ (EO + SI)\ (t) \tag{3.5}$$

Example for t(2):

$$RO(2) = (5.79 + 0)\ - (0 + 0)\ = 5.79$$

RO only can be processed if there is a time period available in the function of MT. RO(1) is 0 because it is not possible to process a maintenance order in the same period because the MT=1.

- Work order (WO) is the moment that the service order is sent to the shop office to do maintenance. This order is:

$$WO(t) \; = \; RO(t + MT) \tag{3.6}$$

where MT is maintenance time in weeks. In this example, MT is 1 week.

Example for t=1:

$$WO(1) \; = \; RO(1+1) \; = \; 5.79$$

- PM order (PWO) is calculated by multiplying the work order and the proportion of preventive maintenance over the total of maintenance in a year. It can be expressed:

$$PWO(t) = \; WO(t) \; * \frac{PM}{(PM + CM)} \; (\text{y}) \tag{3.7}$$

Example for t=1 and y=y:

$$PWO(1) = 5.79 * \frac{180}{(121+180)} = 5.79 * 0.6 = 3.47$$

- CM order (CWO) is calculated by multiplying the order and the proportion of corrective maintenance over the total of maintenance in a year. It can be expressed:

$$CWO(t) = \; WO(t) * \frac{CM}{(PM + CM)}(y) \tag{3.8}$$

Example for t=1:

$$CWO(1) = 5.79 * \frac{121}{(121+180)} = 5.79 * 0.4 = 2.33$$

Example for t=1:

$$CWO(1) = 5.79 * \frac{121}{(121+180)} = 5.79 * 0.4 = 2.33$$

The information of PWO and CWO is transferred to MMRP and CMMS at the end of each period; the system then recalculates the quantity. The sequence of the events in a year or in a week timeframe 1–4 is shown in Table 9.

Table 9. Master maintenance planning schedule—repairable MMPS.

Generator		Year	y-1	y			
		Period	**52**	**1**	**2**	**3**	**4**
Parameters		**Maintenance forecast (MF)**		5.79	5.79	5.79	5.79
Maintenance time (MT)	1	**Ending order (EO)**		5.79			
Lot size	1	**Starting inventory (SI)**		0	0	0	0
Safety stock	0	**Ending inventory (EI)**	0	0	0	0	0
		Rec. order (RO)		0	5.79	5.79	5.79
Proportion		**Work order (WO)**		5.79	5.79	5.79	
PM	CM	**PM order (PWO)**		3.47	3.47	3.47	
0.6	0.4	**CM order (CWO)**		2.33	2.33	2.33	

(3) Maintenance Material Requirement Planning (MMRP)

After the system generates the schedule and corrective planning of maintenance in MMPS, the MMRP module can generate the material purchase planning information.

The quantities of preventive (QMP) and corrective (QMC) maintenance are calculated by the sum of the material that is used in the preventive and corrective maintenance (QMC) divided by the respective number of worker orders in a period. This information comes from CMMS. The planning module consolidates the information and sends it to MMRP. In this example, the Part Number A is used, QMP is 10, and QMC is 7.

The elements of demand for Part Number A of MMPS are:

- Preventive order demand (POD) represents the material that is used in any preventive maintenance per repairable. It can be expressed:

$$POD(t) = QMP \ * \ PWO(t) \tag{3.9}$$

Example for t=1:

$$POD(1) = 10 * 3.46 = 34.6$$

- Corrective order demand (COD) represents the material that is used in any corrective maintenance per repairable. It can be expressed as:

$$COD(t) = QMC * CWO(t) \tag{3.10}$$

Example for t=1:

$$COD(1) = 7 * 2.33 = 16.29$$

- Total demand (TOD) is the sum of the demand in a time frame:

$$TOD(t) = POD(t) + COD(t) \tag{3.11}$$

Example for t=1:

$$POD(1) = 34.6 + 16.3 = 50.9$$

All calculations can be seen in Table 10.

Table 10. Consolidated demand for spare parts.

Part A		**Year**	**y-1**	**y**			
Generator maintenance	QM	**Week number**	**52**	**1**	**2**	**3**	**4**
Preventive	10	PO demand (POD)		34.6	34.6	34.6	34.6
Corrective	7	CO demand (COD)		16.3	16.3	16.3	16.3
		Total demand (TOD)		**50.9**	**50.9**	**50.9**	**50.9**

When the demand is consolidated, it is possible to calculate the amount of material to purchase. In this example, the stock starts with 51.4. The calculation can be seen in Table 11. As previously discussed, regarding the lot size used in MRP, researchers chose to use EOQ because the computational cost is low and the total cost of inventory is near the other models explained by Silver et al. (1998), and Vollmann et al. (2005).

The following assumption is used to calculate EOQ. The average of demand in a period of one year ($\overline{D}$), K is the fixed cost, and H is the holding cost. The EOQ formula is:

$$EOQ = \sqrt{\frac{2K\overline{D}}{H}} \tag{3.12}$$

The following assumption is used to calculate EOQ. For the average of demand in a period of one year ($\overline{D}$), K is the fixed cost, and H is the holding cost. The EOQ formula is:

$$EOQ = \sqrt{\frac{2K\overline{D}}{H}} \tag{3.13}$$

The safety stock (SS) is the safety factor required (z), multiplied by the standard deviation in a period of one year (STD), and the square root of the lead time (Lt).

$$SS = z * STD * \sqrt{Lt} \tag{3.14}$$

In the example, the item has a fixed cost of $50.00 and the holding cost for a week is equal to the price of the item ($20.00) multiplied by the annual rate of 22 percent. Transforming this rate per week, the holding cost is $0.21 and the lead time is four weeks. The average of demand of one year is 50.90. The result is:

$$EOQ = \sqrt{\frac{2 * 50 * 50.90}{0.21}} = 154.86$$

SS= 0 because in this example the standard deviation is 0.

Lot size (EOQ) is rounded up to 155.

Then the elements of MMRP are:

- Total demand (TOD) is the sum of demand in Table 10.
- Ending requisition (ER) is the information when the requisition is active and when the material will arrive. This information comes from TMS and PMS.
- Starting inventory (SI) is the quantity of the stock at the end of the period before:

$$SI(t) = EI(t-1) \tag{3.15}$$

Example for t=2:

$$SI(2) = EI(2-1) = 0.5$$

- Ending inventory (EI) is the quantity of material after processing the quantity that arrived and quantity that is used. It can be expressed as:

$$EI(t) = SI(t) + ER(t) + RR(t) - TOD(t) \tag{3.16}$$

Example for t=1:

$$EI(1) = 51.4 + 0 + 0 - 50.9 = 0.5$$

- Receiving requisition (RR) is when the requisition order will finish and is ready to use. This time is used to make the decision to order or not.

$$if(SI(t) + ER(t) - TOD(t) < SS(t))\ then\ RR(t) = EOQ \tag{3.17}$$

Example t=5:

$$SI(5) + ER(5) - TOD(5) < SS(5) => (2.8 + 0 - 50.9) < 0,\ so\ RR(5) = 155$$

This function can only be processed if the lead time permits.

- Purchasing requisition (PR) is the moment that the purchase order is sent to the supplier. It can be expressed as:

$$PR(t) = RR(t + Lt) \tag{3.18}$$

where Lt is lead time. In this example Lt=4.

Example for t=1

$$PR(1) = RR(1+4) = R(5) = 155$$

The sequence of the events in a year or in a week time frame of 1 to 5 is shown in Table 11.

Table 11. MMRP of Part A.

		Year	y-1	y				
Part A		**Week number**	**52**	**1**	**2**	**3**	**4**	**5**
Parameters		**Total demand (TOD)**		50.9	50.9	50.9	50.9	50.9
Lead time (Lt)	4	**Ending requisition (ER)**			155			
Lot size (LS)	155	**Starting inventory (SI)**		51.4	0.5	104.6	53.7	2.8
Safety stock (SS)	0	**Ending inventory (EI)**	51.4	0.5	104.6	53.7	2.8	106.9
EOQ	155	**Receiving requisition (RR)**		0	0	0	0	155
		Purchasing requisition (PR)		155				

The model calculates the quantity of material to purchase based on the equipment usage and number of maintenance activities that will be performed in a period.

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IV. EXPERIMENTS AND RESULTS

This research uses scenario comparison with full-factorial simulation. The primary goal of this research is to simulate two models in a maintenance environment. The simulations were built because it is difficult to measure and compare a real situation with the new model in a short time.

Two secondary goals of the new model being proposed in this research are to increase the efficiency of inventory control by decreasing inventory costs, and improving response time in an uncertain environment. Figure 11 presents the goal hierarchy plots that "identify resources that will be needed to conduct the simulation study" (Barton, 2010). To achieve the two sub-goals, the researcher needs to identify the factors that affect the cost and response times. Then, research will build and validate a simulator for each model. Once the models are validated, the inventory costs will be analyzed. The completed experiment will produce a simulation with recorded data to support the initial hypotheses and simulate with abrupt demand variation to analyze the response of each model. The experiment summary is in Table 12.

Table 12. Research's experiments.

#	Experiment	Goals
1	Validation (Hypotheses #1, #2)	Validate each model
2	Simulated Data (Hypotheses #3)	Determine which model results in lower inventory costs, with simulated data
3	Recorded Data (Hypotheses #4)	Validate the results of experiment #2 with recorded data (Generalization)
4	Abrupt Variation (Hypotheses #5)	Determine which model is more responsive to abrupt variation in the system

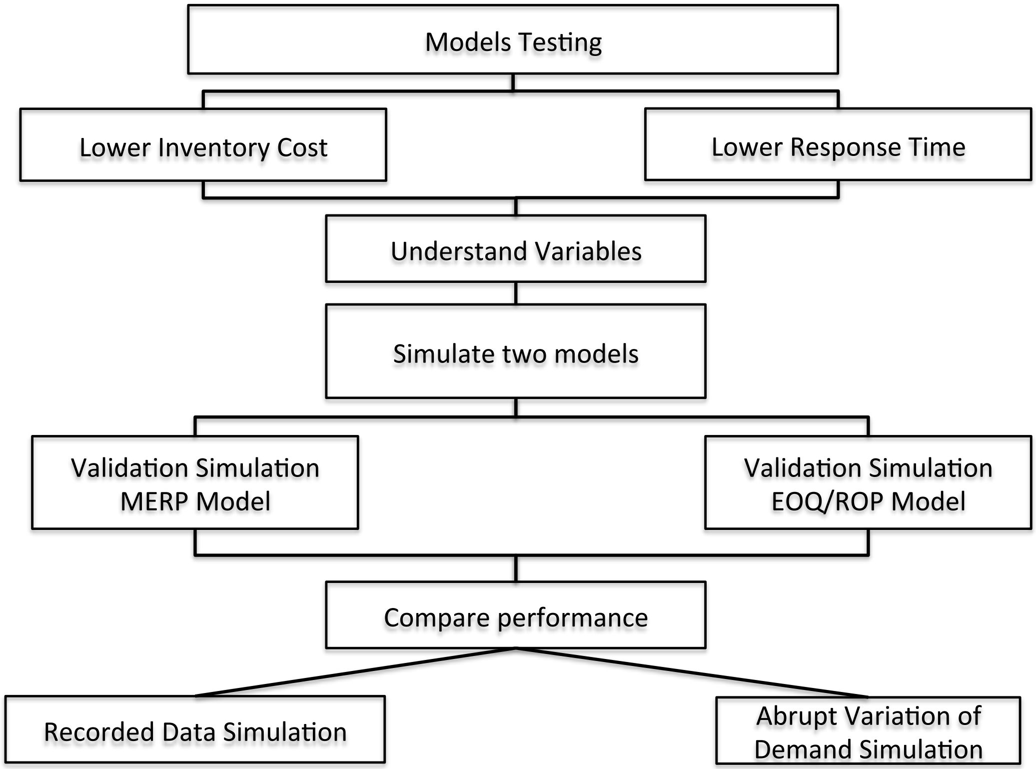


Figure 11. Goal hierarchy plot for the maintenance supply chain study.

A. VARIABLES

The researcher needs to identify the factors that affect the cost and response times. This section will analyze the independent and dependent variables of the research. The author used a cause-effect diagram to identify the variables.

1. Independent Variables for Models

To explain the independent and dependent variables, the researcher uses a cause-effect diagram. The idea is to illustrate the dependent variable and the chain effect relation with the independent variable. Such a diagram is very useful for identifying variables in an experimental study (Barton, 1997).

The dependent variable is the objective of this research, and consists of lowering the inventory costs. In the diagram, the dependent variable is in the end of the tree. The independent variable and nuisance variable (e.g., variables that affect the behavior the

system, but cannot be controlled directly) are the leaves of the tree. The intermediate variable (e.g., variables that are affected by the setting of the independent variable) are the branches (Barton, 2010, p. 79).

Figure 12 presents the cause-effect diagram of the experiment. The cost is affected by the quantity of maintenance in a period, lot size used, uncertainty of the environment, and environment of the system. The independent variable in oval will be able to vary in the experiments.

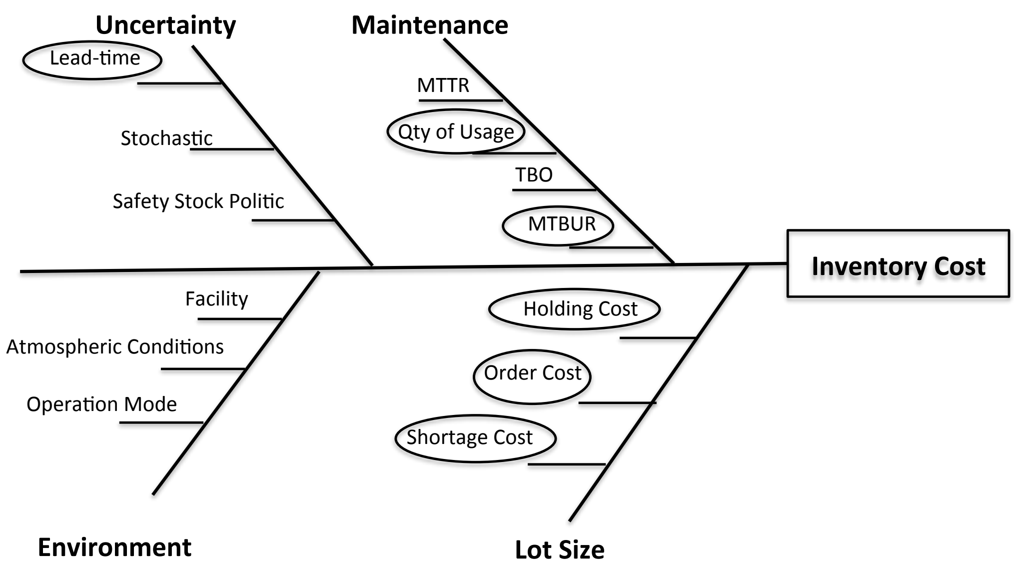


Figure 12. Cause-effect diagram.

In this simulation, the nuisance variable will not affect the experiment because the environment is controlled. The nuisance variables identified are:

- **Atmospheric conditions**: depending on atmospheric conditions (i.e., temperature, pressure, humidity), equipment can require more or less maintenance and the cost of maintenance will be more.
- **Operation mode**: if the equipment is operated in an extreme manner (e.g., at the limits of its designed tolerances, for extended periods, etc.), the attrition is high or vice-versa and, consequently, there is more or less maintenance.
- **Facility**: depending on the facility, there is more capability to do maintenance or to supply the need and increase the item availability.

Some independent variables in the experiment will be fixed because the study looks to observe the patterns of how those others variables affect the inventory costs. The fix independent variables are:

- **Mean time to repair (MTTR)**: depending on the shop and facility, the maintenance time can be more or less. This affects the quantity of equipment that the management should have to match the availability of the system. In the experiment, the MTTR will be fixed.
- **Time between overhaul (TBO)**: in the experiment, the value will be fixed, because this event does not change with uncertainty. The idea is to calculate the quantity of preventive maintenance in a time-period. The TBO will be 3,000 hours in all experiments except the third experiment.
- **Safety stock policy**: Safety stock is related to the risk of material shortage. Safety stocks can be based on minimizing cost, customer service and aggregate consideration (Silver et al., 1998, pp. 241–242). In this study, it is important to consider the time that there is a shortage because it affects the availability of the system. The study tries to minimize the cost, and to increase the availability of the system it will charge a value per short per unit time. The formula that the experiments use to find the z value is the formula (2.9) (Silver et al., 1998, p. 266).
- **Stochastic demand**: to simulate the uncertainty, the simulation causes the same stochastic uncertainty in the mean of each demand event using a random Poisson distribution. The algorithm that produces this distribution is in the appendix B.

The independent variables that will change are:

- **Order factor cost (H)**: K is incurred every time that there is an order. The lot size changes depending on the order cost and holding cost. The idea is to simulate three values based on the price of the item to observe the effect on the inventory costs (high, intermediate, low).
- **Holding factor cost (H)**: h, also referred to as an inventory carrying cost, "is accumulated per unit held in inventory per day that the unit is held" (Simchi-Levi et al., 2007). Eighty percent of holding cost is capital cost (Ballou & Srivastava, 2007, p. 348). Other variables compose the rest of the holding cost, such as insurance, shelf life limitations, and operating cost involved in storing inventory or the cost of operating a warehouse facility (Vollmann et al., 2005, p. 138). In this experiment, the holding cost can vary from 5 to 30 percent per year. When the EOQ model is used, lot size changes depending on the order cost and holding cost. The idea is to simulate three values to observe the effect in the inventory costs (high, intermediate, low).

- **Shortage cost (S)**: occurs when demand exceeds the available inventory for an item. It is related to the level of customer service that the organization wants to reach. It can be like a missed chance of profit, which is called the opportunity cost. Depending on the penalty that the manager will charge for the shortage of the material, the inventory costs will be affected more or less. The idea is to simulate three values based on the price of the item (high, intermediate, low).
- **Quantity of usage (#U)**: represents an average quantity of usage that the system will perform in a period (high, intermediate, low). The maintenance can be measured by frequency or elapsed time. This experiment will use the quantity of maintenance by elapsed time (e.g., aircraft maintenance occurs after 100 hours flown, generator TBO occurs after 3,000 hours flown). To change the quantity of maintenance in this experiment, manipulate the quantity of hours per month that an aircraft flies. Generally, an airplane flies six days a week (48 hours), and 192 hours monthly. Therefore, the research starts the range (low) with 5 hours monthly, intermediate with 125 hours and very high with 205 hours.
- **Lead time (Lt)**: the length of lead time affects the capacity of the model to match the needs. Long lead time means that there will be more uncertainty in the environment. The idea is to simulate three values to observe the effect on the inventory costs (high, intermediate, low).
- **Mean time between unscheduled removals (MTBUR)**: The ideal is to fluctuate the value that will increase the number of corrective maintenance causing more uncertainty. The variation will be based on the percentage rise or fall in TBO. Although the MTBUR is affect by TBO, in this research it will be treated as independent, so that TBO and MTBUR are independent for each repairable item.

The K, S independent variables vary based on the percentage of the item price. The item price will be set to $20.00 in all experiments except the third experiment. The MTBUR vary based on the percentage of the Time Between Overall (TBO). The TBO will be set to 3000 hours in all experiments except the third experiment. The independent variable will range as follows according to Table 13.

Table 13. Independent variable range.

K	H	S	# U	Lt	MTBUR
100%	30%	100%	225	30	25%
15%	22%	50%	125	15	100%
5%	5%	20%	5	5	200%

All the independents variable will test in two scenarios that represents the rule that managers can use to decrease the costs associated with maintaining an inventory and meeting customer demand (Hillier & Lieberman, 1980). These scenarios will be used in the experiments to compare cost between the models. There are two scenarios: EOQ/ROP model and MERP model.

1. **Maintenance enterprise resource planning (MERP)**: represents a model that increases the capacity to process information by connecting lateral and vertical information in the elements of the supply chain to work as a system. The model was explained in the preceding section.
2. **Economic order quantity (EOQ/ROP)**: this model represents a continuous review policy (Q,R); whenever inventory levels fall to a reorder level (ROP), an order for Q units is placed (Simchi-Levi et al., 2007).

2. Dependent Variable

Inventory cost is the dependent variable that is used in all experiments. To calculate the inventory costs, this research uses three components: holding cost, fixed cost, and shortage cost. Following is an explanation of each cost component:

- Total order cost: the sum of order costs incurred in a period (N) multiplied per fixed cost.

$$C_k = K * N \tag{4.1}$$

N is the quantity of order in a period.

- Total holding cost: the sum of held stock in a period (I) multiplied by holding cost.

$$C_h = I * H \tag{4.2}$$

- Total shortage cost: in this research, this cost is the quantity missed (M) of the item in period times and the penalty chosen that is in function of the price of the item (S). To count the quantity missed in a period, the calculation will be the sum of negative stock. The decision is made to penalize the long-time negative stock that can affect the availability of equipment. So, if the item missed 1 unit in day 1, and missed 1 unit again in the day 2, the M will be 2.

$$C_s = M * S \tag{4.3}$$

- Total cost (TC): is the sum of the fixed, holding and shortage costs. It is represented in the following formula:

$$TC = C_k + C_h + C_s \Rightarrow TC = K * N + H * I + S * M \tag{4.4}$$

An example of the total cost calculation is shown in Table 14.

Table 14. Total cost calculation.

	Sum of qty negative stock in a period	***Qty ordered in a period***	***Sum of qty positive stock after in a period***
Qty	100	39	21,360.10
Parameters	S=20	K=54	h=0.4
Total cost	**Total shortage cost**	**Total order cost**	**Total holding cost**
12,650.04	2,000.00	2,106.00	8,544.04

B. EXPERIMENTS

The research consists of four experiments. Experiment 1 seeks to simulate and validate each model using regression analysis. After the models are validated, the second experiment seeks to compare the inventory costs by using a dependent t-test to compare the means. In the third experiment, some independent variables will be fixed, and recorded data from Brazilian Air Force maintenance operations will be used to compare the inventory costs. In the last experiment, the researcher will simulate abrupt variations of an independent variable to observe the response time of models. This section explains the procedure that researcher used to increase the reliability and validity of the research and result of each experiment.

1. Experiment 1—Validation

According to Law & Kelton, "simulation is a computer-based statistical sampling experiment to produce the answers" (1991, p. 523). The objective of the first experiment is to validate the relationships between the variables in each model with the dependent variable, which means if y is related to any of the x (independent variables). Although the range of independent variables is not linear, the output with the independent variables is. The model of each simulation can be represented for the following multi-linear regression equations:

$$Y_{merp} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \varepsilon \tag{4.5}$$

$$Y_{eoq/rop} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \varepsilon \tag{4.6}$$

where x_1 is order cost, x_2 is holding cost, x_3 is shortage cost, x_4 is usage quantity, x_5 is lead time, x_6 is MTBUR, and ε is the error. Y_{merp} is MERP model total cost and $Y_{eoq/rop}$ is EOQ/ROP model total cost.

a. Experiment Design

The study uses factorial design where each factor (combination of the values of the independent variable) is simulated and tested. In this experiment, each factor (independent variable) has three levels, so that the experiment can have $3^6 = 729$ situations (S). Each simulation uses a Poisson random distribution in the demand of corrective maintenance and demand of spare parts of corrective maintenance to simulate the uncertainty.

As the simulation outputs are stochastic, a single run of each simulation is an unreliable approach. In the experiment, there are six β coefficients in the model and the variance ε to estimate. The researcher wants to test the overall fit of the regression model and individual independent variable within the model. To validate the model, the researcher follows Field's (2009, p. 222) formula to find the minimum sample size of the replication to each situation to have great power to detect the effect of the variables:

$$R = 104 + k \tag{4.7}$$

K is the number of independent variables. In this case, R is 110.The simulation will repeat each situation 110 times. Each situation will have:

$$S_1 = y_{11}, ... y_{1i}, ... y_{110}$$

Replication (R) allows for checking the adequacy of the model (Barton, 2010). Each model will produce 80,190 samples (O).

The representation of the experiment for each model is:

S_1^{729} R_1^{110} ---------------Model-----------------------O

b. *Simulation*

The research will simulate the inventory costs of each model, with a different level for each independent variable. This experiment controls all internal threats and seeks to study the relations “under a pure and uncontaminated condition” (Kerlinger & Lee, 1999, p. 581).

The purpose of the simulation experiment is to test the hypotheses derived from the theory. The weakness of generalizing the hypotheses is compensated for with strong internal validity (Kerlinger & Lee, 1999). The simulation seeks to represent the reality of an environment. The simulation manipulates the independent variables and records the dependent variable for analysis. This kind of experiment allows for “all of the roles of the research scientist without having to contend with the time-consuming process of data collection” (Benedict & Butts, 1981).

The time-period of the experiment is four years, (y-2, y-1, y, y+1). In each year, it will set up the daily average usage to process the quantity of maintenance. In y-2 and y-1, it will calculate the demand of corrective and preventive maintenance, the spare part consumption of the maintenance, and the daily average. In the y and y+1 are simulated 365 events for each year, with 730 events for simulation. Then, the resulting experiment is recorded.

The simulator was programmed using Visual Basic for Application with Microsoft Excel. The Excel is used to produce a useful and convenient analyzer tool (Hihn, Lewicki, & Wilkinson, 2009). It permits easy testability and repetition of the experiment. The simulation was programmed to produce 110 samples for situations producing 80,190 samples.

The simulator uses many Excel worksheets to process, record, and analyze the information. The first step is to fill each combination of independent variables and fix parameters. With this information, the quantities of preventive and corrective maintenance per year are calculated (maintenance and operation planning—MOP

function). Based on the daily average of maintenance, the simulator generate produces a random Poisson number/quantity of corrective maintenance per day to represent the uncertainty.

To calculate the material of preventive maintenance, the simulator multiplies the number of preventive maintenance in a period per the number of material that the maintenance needs. To calculate the material of corrective maintenance, the simulation takes the number of corrective maintenance in a period, and multiplies this value per the number of material maintenance required. The result is applied to a Poisson distribution to generate uncertainty again. The sum of spare parts of preventive and corrective maintenance is the total material used in the maintenance in a period. This value is used to decrease the inventory in both experiments.

The EOQ simulation used the data from independent variables (K, H) and the demand as the average of the past 30 days to calculate EOQ. For the ROP, the system calculates the average demand of the 30 days before and uses a safety factor to minimize the shortage. Equation 2.9 is used to find the z value. With EOQ, ROP information, and the total material used in the maintenance, the experiment simulates two years of consumption and replacement of stock.

MERP simulation uses the same quantity of maintenance used in the MOP to generate the Maintenance Master Planning Schedule (MMPS). Afterwards, it generates the list of spare parts to purchase based on techniques of maintenance material required planning (MMRP). To decrease the daily stock, the simulation uses the same quantity of spare part used in the EOQ simulation. The safety stock of the both experiment uses the formula 2.19.

At the end of each procedure, the EQO and MERP inventory costs and quantities are recorded, and the simulator repeats the experiment 110 times with random maintenance and consumption of material. After recording 110 samples, the simulator changes the parameters and processes again until finishing the last parameter. A sample

of the simulation result is provided in Appendix D. An overview of the simulation is in the Appendix E. The simulation is available with the researcher if someone needs. The procedure is shown in Figure 13.

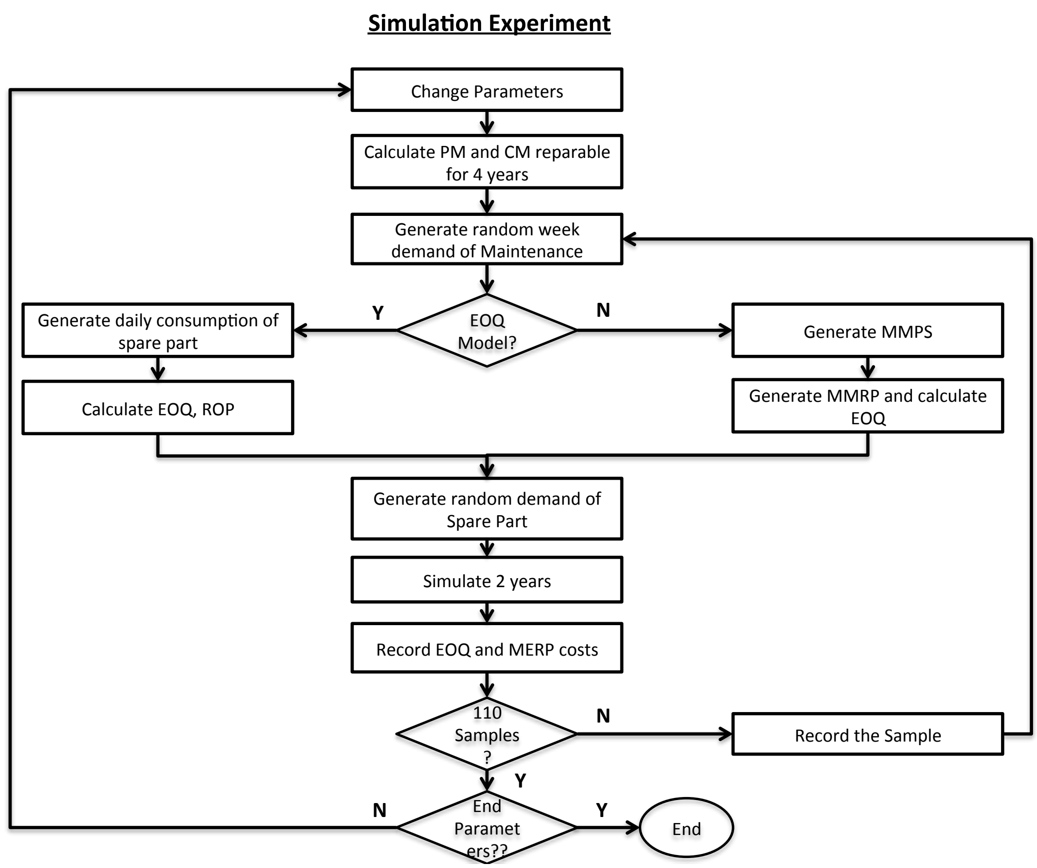


Figure 13. First, second, and fourth experiment simulation procedures.

c. *Statistical Test*

In the first experiment, the research wants to check if the models predict inventory cost accuracy. The first hypothesis is:

H_0 : The EOQ/ROP and MERP model do not predict the inventory costs accurately.

H_1 : The EOQ/ROP and MERP model predict the inventory costs with significant accuracy.

The hypothesis is tested by comparing the amount of variation explained by the independent variables to the amount of variation left unexplained using F statistic ratio

(F=Regression explain variation/unexplained variation). The research will use analysis of the variance table (ANOVA) to discuss this result (Field, 2009, pp. 206–209). The test is to verify if at least one coefficient β is different from zero, the null hypothesis is all β is equal to zero.

The second hypothesis is to test whether all independent variables affect the inventory costs in both models. The research will test the marginal contribution of an individual independent variable when all other variable are included in the model. For the testing of individual contributions of the independent variable for each model, test the following hypotheses for $\beta_{1\rightarrow 6}$ for:

H_0 : β does not affect the inventory costs (equal to zero)

H_2 : β contribution affects the inventory costs (different from zero)

The multicollinearity between the independent variables will be tested by the variance inflation factor (VIF) that "indicates whether a predictor (independent Variable) has a strong linear relationship with the other predictor(s)" (Field, 2009, p. 224). As parameter for VIF >5, there is a suspicion of multicollinearity.

d. Assumption of the Simulation

Assumptions for both models:

1. The cost does not change significantly with time.
2. Deliveries do not have uncertainty.
3. The decisions will occur daily.
4. The experiment applies uncertainty only to the demand requirement (requirement for more or less than planned using a random Poisson distribution)

The parameters are shown in Table 15.

Table 15. Fixed parameters—first and second experiments.

Fixed parameter	Value
Item price	$20.00
Time Between Overall (TBO)	3000 hours
Safety Stock	Both models follow Equation 2.19
Number of aircraft	300
QPA of generator in aircraft X	2
QM of part A in preventive maintenance of generator	QMP = 10 probability of change = 100%
QM of part A in corrective maintenance = 10	QMC = 10 probability of change = 80%
Stock Initial both model	ROP of 4 days before the year (y)
Frame time of experiment	365 day/year

e. Result Analysis

To analyze the models, the researcher discusses the regression assumption and analyzes the *F*-ratio and *b* -coefficients of each model.

(1) Statistical Assumptions Analysis

The experiment consists to run 110 times, including 729 situations of each model. Each time the simulation initializes a new random Poisson distribution to produce uncertainty in the corrective maintenance. The inventory cost (IC) is the dependent variable of the experiment.

The independent and dependent variables match the following assumption. The independent variables are quantitative with variation in value and do not have a relationship between two or more of the independent variables with VIF=1 to all independent variables. The variables are uncorrelated with external variables. The outcome variables are "quantitative continuous and unbounded" (Field, 2009, pp. 220–221). Besides the assumptions reported, the researcher checked normality, multicollinearity, and homoscedasticity for each model (EOQ, MERP).

Multicollinearity tests shown in Table 16 revealed that the VIF values are less than 5. Thus, the test indicates that the independent variables do not have a strong linear relationship with the other predictors.

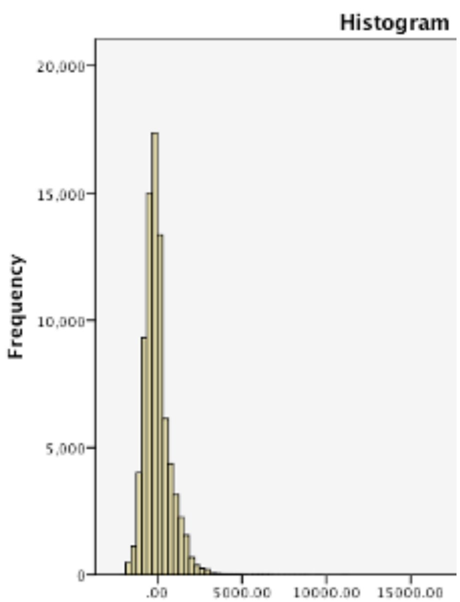
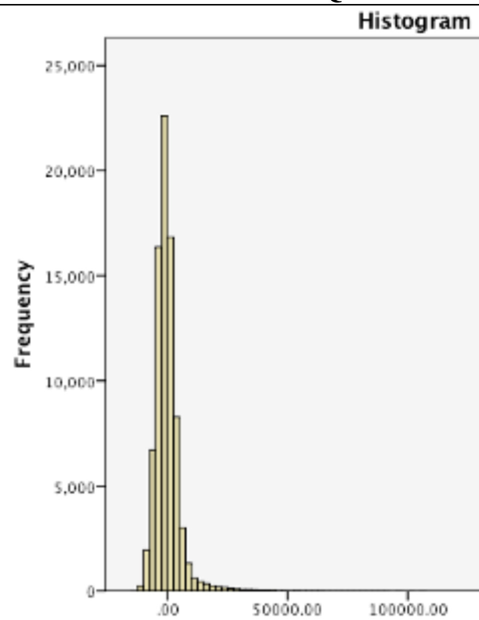
For normality, using the Kolmogorov-Smirnov (K-S) test, the researcher found the significance value ($p < 0.05$), which indicates a deviation from normality. The results of this test, which are shown in Table 16 **Error! Reference source not found.**indicates that both models have p less than 0.05. However, the researcher cannot affirm that this distribution is not normal. For large samples, the K-S test can be significant even when the score deviates only slightly (Field, 2009, p. 148). According to the results in Table 17, the distribution of both models has a slightly positive skew. The curve is not an exact normal but the residual results are symmetric around the mean that is roughly 0; it looks like the residuals meet this assumption. Even if it fails the *p*-value test, the histogram of the residual looks symmetric and the research can say that the model follows the normal distribution.

The homoscedasticity test using Levene's test, on the other hand, showed a real problem. For the MERP model, the inventory cost variance shows $F(2, 80{,}187) = 2{,}417.18$, $p<0.01$. For the EOQ model, the inventory cost variance shows $F(2, 80{,}187) = 508.84$, $p<0.01$. This result indicates that the variance is significantly different. However, the test is to compare the models; the result of this test indicates the models are worse at predicting larger costs than predicting smaller costs. Therefore, this finding does not mean the models are not useful. It really means that if the models predict a high cost, the actual cost may or may not be high. Besides this argument, the same problem that happened in the K-S test, "when the sample is large, small differences in groups' variances can produce a Levene's test that is significant" (Field, 2009, p. 152). Another argument is that the Levene's test is a one-way ANOVA test, and it is "fairly robust in terms of the error rate when sample sizes are equal" (Field, 2009, p. 360). Based on the arguments presented, the researcher considers that the results attend the assumptions.

Table 16. Assumption regression result experiment 1.

Test						
Multicolinearity						
	VIF					
	K	**H**	**S**	**U**	**LT**	**MTBUR**
MERP	1.00	1.00	1.00	1.00	1.00	1.00
EOQ-ROP	1.00	1.00	1.00	1.00	1.00	1.00
Normality						
	Kolmogorov-Smirnov					
	Statistic	**df**	**Sig.**			
MERP	0.152	80,190	0.000			
EOQ-ROP	0.271	80,190	0.000			
Homogeneity of Variance						
	Levene					
	Statistic	**df1**	**df2**	**Sig.**		
MERP	2,417.179	2	80,187	0.000		
EOQ-ROP	508.836	2	80,187	0.000		

Table 17. Normality charts.

IC MERP	IC EOQ
	
Mean= -4.79E-12 Std. Dev = 856.26 N = 80,190 Skewness=3.161	Mean = 1.35E-11 Std. Dev. =6627.89 N = 80,190 Skewness=6.099

(2) Hypothesis Analysis

The goal of the first experiment is to validate the models to compare the means of each model in the next experiments. The results in Table 19 show that the average of inventory cost (IC) of EOQ model (m=5134.83, se=56.35) is larger than the average of the MERP model (m=1,588.94, se=41.02).

The R square shows that for the EOQ model the independent variable can explain 36.3 percent of the variation of inventory costs. For the MERP model, the independent variable can explain 67.4 percent. The variance of both models explains the R square. The variance of the EOQ model (s=8,303.33) is larger, which explains why the R square is low. The MERP model variance (s=1,500.43) is lower. This means that it is easier to explain the variance in the MERP model than in the EOQ model. The models have a great difference of variance, but the means can be compared.

To explain the R square only, the research performed two more tests. For the first test, the EOQ simulation used the same situation but without uncertainty (Random Poisson). In the second test, the range of independent variables was linear and without uncertainty (Random Poisson) too. Both tests have 729 results, and the R square comparison is shown in Table 18.

Table 18. R square test.

R Square Experiment 1	R Square Test 1	R Square Test 2
0.363	0.743	0.938

The next discussion of the models arises from the ANOVA test Table 19 shows the test for inventory costs of the EOQ model (F=7,610.50, p <.001, ω =.60) and the MERP model (F=27,670.32, p <.001, ω =.82). F-ratio "explains how much variability the model can explain relative to how much it can't explain" (Field, 2009, p. 209). Since that p value is so low, the researcher rejects the null hypothesis and can conclude that at least one of the six variables has a nonzero regression coefficient. Then, there is a less than 0.1 percent chance that the null hypothesis is true. Therefore, both regression models overall have a significantly high degree of predictability of the inventory costs with large effect size.

Even though the t-statistic is statistically significant, this doesn't mean that the effect is important (Field, 2009, p. 332). Research uses the measure of effect size (*r*) to provide the importance of an effect (Field, 2009, p. 56); *r* is "simply an objective and (usually) standardized measure of the magnitude of observed effect (Field, 2009, p. 332).

Effect size helps to understand the magnitude of differences found. Effect size measures either measure the sizes of associations or the sizes of differences. For effect of measure, r=0 means no effect, around .10 represents small effect, around .30 represents a medium effect, around .50 represents a large effect, and 1 means that there is a perfect effect (Field, 2009, p. 57). You can think of effect sizes as differences in standard deviations. Performing an analogy, a large effect size is an effect that can be observed

with the naked eye, small effect size is something that happen in the world but need precious instruments to observe.

To calculate the effect size using ANOVA, the authors uses omega squared ω^2 that calculate the effect size based on the variance explained by the model, and the error variance that is represent for this formula (Field, 2009, p. 389):

$$\omega^2 = \frac{SS_M - (df_M)MS_R}{SS_T + MS_R} \tag{4.8}$$

where SS_M model equals the sum of square, df_M is the degree of freedom, SS_T is the total amount of variance in the data, and MS_R is the mean square error.

The other statistical test is to verify the individual contribution of each independent variable in the model when all other variables are included. Table 19 shows the B value and t-test of the independent variables for each model (p<0.001). The "*b*-value shows the gradient of the regression and the strength of the relationship between a predictor and the outcome variable" (Field, 2009, p. 209). The researcher concludes that p-value < 0.001 is the value for all the independent variables, and the probability of the B factor is equal to zero or is less than 0.1 percent. Therefore, the independent variables of both models make a significant contribution (p<0.001) to predicting inventory costs.

Table 19. Statistical result from experiment 1.

Inventory Cost Experiment 1						
	Descriptive Statistics					
	EOQ/ROP			**MERP**		
Mean	5,134.83				1588.94	
Std. Deviation	8,303.33				1500.43	
N	80,190				80,190	
Std Error	56.35				41.02	
	Model Summary					
	EOQ/ROP			**MERP**		
	R	**R Square**		**R**	**R Square**	
	0.602	0.363		0.821	0.674	
	ANOVA					
	EOQ/ROP			**MERP**		
	F	**Sig.**	***ω***	**F**	**Sig.**	***ω***
	7,610.50	.000***	0.60	27,670.32	.000***	0.82
	Coefficients					
	EOQ/ROP			**MERP**		
	B	**Std. Error**	***t***	**B**	**Std. Error**	***t***
(Constant)	-6672.27	90.04	-74.103	-1,038.86	11.63	-89.308
K	-42.52	2.75	-15.486***	51.45	0.36	145.047***
H	379,685.48	4097.74	92.657***	110,408.18	529.39	208.556***
S	187.00	3.55	52.726***	20.72	0.46	45.222***
# Usage	28.74	0.26	110.414***	8.62	0.03	256.358***
Lead Time	301.15	2.28	132.188***	30.37	0.29	103.183***
MTBUR	-0.72	0.01	-66.278***	-0.21	0.00	-151.909***

***p<0.001

2. Experiment 2—Simulated Data

After the validation of models, the objective of the second experiment is to compare the inventory costs between the two models to answer the research question.

a. Experiment Design

The study uses the same experiment design as the first experiment. Now, the researcher will take the result of both experiments and compare the results. The factorial design is three levels of six factors with 110 replications where the factorial will be tested in two scenarios (EOQ/MERP):

S_1^{729} R_1^{110} ---------------X(EOQ)----------------------O

S_1^{729} R_1^{110} ----------------X(MERP)---------------------O

b. Simulation

The simulation uses the same process as the previous experiment.

c. Statistical Test

To compare the inventory cost models, the study will test the following hypothesis:

H_0 : MERP increases or keeps the same inventory costs compared to EOQ/ROP. $IC_{MERP} \geq IC_{EOQ/ROP}$

H_3 : MERP lowers inventory costs compared to EOQ/ROP. $IC_{MERP} < IC_{EOQ/ROP}$

To test this hypothesis, the study uses the dependent t-test (paired t-test) to compare the means of the inventory costs of the both models. It uses the dependent t-test because the simulator measures the inventory costs of both models using the same situation (i.e., same consumption of material and work order parameter). So, the samples are not independently randomly selected; instead there is an observation for each individual situation in each model, so the data are paired (Field, 2009).

d. Assumption of the Simulation

The assumption is the same as in experiment 1.

e. Result Analysis

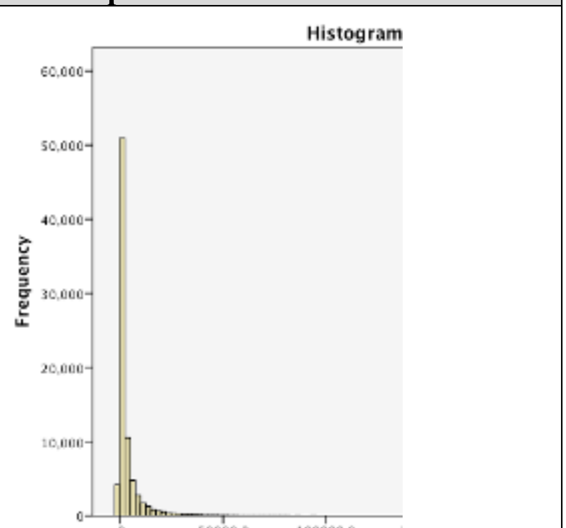
To compare the models, the researcher discusses the dependent t-test assumption and the result of comparison.

(1) Statistical Assumptions Analysis

The dependent t-test is used when there are two experiments, and the data comes from the same condition (Field, 2009, p. 325). In our case, the demand and uncertainty are the same; only the model to manage the inventory is different. The dependent t-test has as its assumption the normality.

To check whether the difference is normally distributed, the researcher calculates the difference between the inventory costs results of each model and verifies the distribution of these differences. The experiment's histograms of the difference in the dependent variable are shown in Table 20. According to Field, "if the samples contain more than 50 scores, the sampling should be normally distributed" (Field, 2009, p. 327). In experiment 2, each situation is repeated 110 times, and there are 80,190 samples. Field (2009) affirms: "use a big sample and [do] not worry about normality" (Field, 2009, p. 329). Based on Table 20 and the arguments previously identified here, the researcher can infer that the data are normally distributed.

Table 20. Histogram of difference—experiment 2.

Experiment 2—Difference IC


(2) Hypotheses Analysis

After validation of the model in the first experiment, the researcher can test two groups of means from the models using the dependent t-test. For the second experiment hypothesis 3 is tested, and the result shows that on average the predicted inventory costs is significantly lower using the MERP model (M=1,588.94, SE=5.30) than it is from the EOQ/ROP model (M=5,134.83, SE=29.32), $t(80,189)=133.92$, $p<.001$, $r=.43$. The result is Table 21.

Table 21. Dependent *t*-test results experiment 2.

Exp. 2 - IC	MERP	EOQ
Mean	1,588.94	5,134.83
Std. error	5.30	29.32
mean diff	3,545.89	
N	80,190	
t	133.92	
sig	.000***	
r	0.43	

***p<0.001

The researcher can reject the null hypothesis and conclude that the inventory costs predicted by the MERP are significantly lower than that of the EOQ/ROP model, which represents a substantive finding. The formula to calculate the effect size using *t*-test is:

$$r = \sqrt{\frac{t^2}{t^2 + df}} \tag{4.9}$$

3. Experiment 3—Recorded Data

Experiment 3 is intended to verify if the conceptual simulation model that was done in the second experiment can be repeated with real data. The question is, "is the conceptual simulation model an accurate representation of the system under study?" (Kleijnen, 1995). For the simulation study, there are two steps to determine whether a model is an accurate representation of the system: verification and validation.

For this research, "verification is determined that a simulation computer program performs as intended" (Law & Kelton, 1991, p. 299). This procedure was done in the first and second experiment. According to Law and Kelton, "Validation is concerned with determining whether the conceptual simulation model is an accurate representation of the system under study" (Law & Kelton, 1991, p. 299).

a. Experiment Design

Experiment 3 uses the range of independent variables presented in Table 22. Using these independent variables, the experiment will simulate the real data to compare the models. Each situation (set of independent variables) will be simulated with 490 repairable maintenance data from the Brazilian Air Force to compare the inventory costs.

Table 22. Set of independent variables for experiment #3.

K	H	S
100%	30%	100%
15%	22%	50%
5%	5%	20%

In this experiment, the independent variable "quantity of usage" (#U) and MTBUR will not be used, because the recorded data results from these variables. The lead time will be fixed to measure the variation based on the cost factors, rather than the lead time uncertainty.

The study will simulate maintenance (WO) and consumption material data from 490 repairable items to compare the record cost. Then, this experiment will test 3^3 =27 situations with 490 sets of repairable data (A), each with a total 13,230 samples of each model. The design representation is:

$$S_1^{27} \; A_1^{490} \quad \text{---------------X(EOQ)-----------------------O}$$

$$S_1^{27} \; A_1^{490} \quad \text{---------------X(MERP)---------------------O}$$

b. Simulation

(1) Procedure of Data Selection

The real data comes from an ERP system of the Brazilian Air Force (BAF) that is called the Integrated Logistics System of Material and Services (SILOMS). This system was developed in-house at BAF and has been used throughout the logistics units of the Air Force since 1998.

The requested data were related to work orders and material consumption from 2010 until 2013, simulating four years (y-2 to y+1). Data represent the repairable maintenance (work order-WO) and material consumption in the WO that were performed at BAF.

The information came in two spreadsheets. The first worksheet refers to work orders from repairables, and contains identification information of the repairables: PN + CFF, total preventive (PWO), and weekly corrective (CWO) work order quantity. The representation is in Table 23.

Table 23. Service order data structure.

PN	CFF	Description	Week	CWO	PWO
13419A	F0189	MONTANTE Left	2010-01	3	2

Table 24 contains the data representing the PN repairable and the PN spare part identity that are used in the work order. For each selected PN repairable, there was a PN spare part with the quantity that was consumed in a week, and the price of the PN spare part. The PN spare part selected was the most commonly used in maintenance from 2010 to 2013. This criterion was used to obtain most historic consumption data for use in the models of the study.

Table 24. Consumption material data structure.

PN	CFF	PN spare part	CFF spare	Desc	Qty CWO	Qty PWO	Price $
13419A	F0189	DLS4-00587	0079K	Bolt	10	12	15.62

For this research, the data studied was that which related to the repairables that had been through performance maintenance in the BAF between 2010 and 2013. During that period, there were 1,624 different repairables with maintenance, 1,284 that had been through performance in BAF, and 340 had been through performance in private companies.

To define the size sample, the author chose to follow Table 25. Following Christensen (2008, p. 242), N is the size of the population, n is the size of the recommended sample. With the population of N=360 repairable, the sample size recommended to 95 percent of confidence level is circa of 180, N=50,000, n=384. The author chose more than 384 samples, because the BAF database contained a large sample quantity. Based on samples came from Brazilian Air Force, the author chose 500 samples of repairables with their respective work orders and consumption of spare parts.

Table 25. Sample size for populations (after Christensen 2008, p. 242).

N	n	N	n	N	n	N	n
10	10	120	92	1,200	291	50,000	384
50	44	360	186	3500	346	500,000,000	384

To choose 500 repairables, each register received a sequential identification number. Using a random generation of Excel spreadsheet numbers, from 1 to 1,284 was chose 500 numbers of repairables registers. The author had to delete 10 registers because the data information was inconsistent. After these procedures were completed, the experiment consisted of 490 sample PN repairable parts, and 490 PN spare parts. The sample of experiment data is provided in the Appendix C.

A second spreadsheet was created using 490 repairables and spare parts, and included work orders (WO) and material consumption per week from 2010–01 to 2013–52. Table 26 presents the WO and consumption of material per period. The 490 repairables and spare parts generated more than 101,920 registers of WOs, and the same consumption of material data, performing a total of 203,840 registers.

Table 26. Work order and consumption of material per week.

PN	Week	CWO	PWO	PN spare	CWO	PWO
RFN3934	2010-01	3	0	3040110	0	0
RFN3934	2010-02	0	0	3040110	10	0
RFN3934	2010-03	5	2	3040110	0	20
RFN3934	2010-04	0	0	3040110	0	0

(2) EOQ Simulation Procedure

Simulations will calculate the inventory costs for each situation with real data samples. The experiment consists of 27 situational simulations, with 490 samples each, that record the inventory costs of each model. Each model calculates the inventory costs for 2012 and 2013.

Simulator EOQ/ROP uses the average historical consumption from 2010 and 2011. The simulation calculation is the same one that was performed in previous experiments. In the previous simulations, Poisson distributions are used to simulate the demand, while this experiment uses the actual demand (AD). Thus, the EOQ and ROP are simulated based on historical consumption material, and use the recorded data to simulate demand consumption during the period 2012–2013. Table 27 presents the simulator data in weeks 5 and 6.

Table 27. EOQ/ROP real data simulation.

	Week	AD	EOQ	ROP	ER	SI	EI	RR	PR	Transit
							-			
Y	5	2	13.66	4.56	0	13.17	11.17	0	0	0
	6	0	13.17	4.56	0	11.17	11.17	0	0	0

(3) MERP Procedure

The MERP simulator used the preventive and corrective work orders from the BAF. To calculate the average of material that was spent on preventive and corrective maintenance (QMP and QMC), the simulator summarizes the material consumed in 2010 and 2011, and divides each per WO for this period. For 2012 and 2013, the simulator

predicts the spare parts by multiplying the number of work orders per QMP and QMC. The total demand (TOD) is the week 5 is 1.10. The calculation of spare parts forecast is in Table 28.

Table 28. MERP spare part demand calculation.

	2012	**2013**						
QMP	0	0						
QMC	1.10	1.10						
		PWO	**CWO**	**Week**	**AD**	**QMP *PWO**	**QMC* CWO**	**TOD**
2012	5	-	1.00	5	2	0.00	1.10	1.10
	6	-	-	6	0	0.00	0.00	0.00

The simulation calculation is the same one that was performed in experiment 1 and 2. The previous simulations used Poisson distributions to simulate the demand, while this experiment uses the actual demand (AD) shown in Table 28. Thus, the simulator simulates the predicted demand using WO and historical consumption material from actual data. Next, the simulator uses recorded data to simulate consumption demand during the period 2012–2013. Table 29 presents the simulator data from weeks 5 and 6 in 2012.

Table 29. MERP inventory control simulation.

Week	ER	EOQ	SI	EI	RR	PR
5	-	22.98	13.17	13.17 11.17	0	0
6	-	22.98	11.17	11.17	0	0

c. Statistical Test

To compare the inventory cost models, the study will test the following hypothesis:

H_0 : MERP increases or keeps the same inventory costs compared to EOQ/ROP. $IC_{MERP} \geq IC_{EOQ/ROP}$

H_4 : MERP lowers inventory costs compared to EOQ/ROP. $IC_{MERP} < IC_{EOQ/ROP}$

The hypothesis test will be the same one that was used in the second experiment.

d. *Assumption of the Simulation*

Assumptions for both models:

1. The cost does not change significantly with time.
2. Deliveries do not have uncertainty.
3. The price of each item comes from real data of the BAF.

Table 30. Fixed parameters of experiment 3.

Fixed Parameter	Value
Safety factor to EOQ	90%
Safety Stock	Both models follow the equation 2.19
Lead time	4 weeks
Sock initial of both model	ROP of 4 week before the year =”y”
Time frame of experiment	52 week/year

e. *Result Analysis*

To compare the models, the researcher discusses the dependent t-test assumption and the result of comparison.

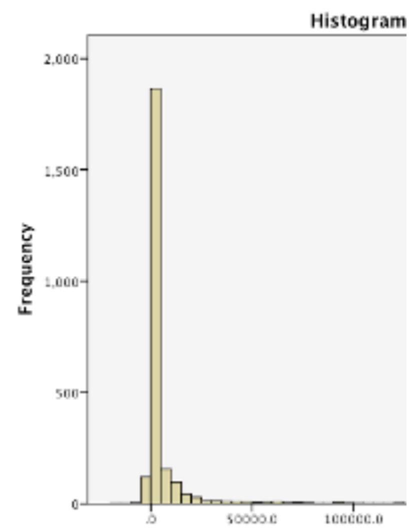
(1) Statistical Assumptions Analysis

To check if the difference is normally distributed, the researcher calculates the difference between the inventory cost results of each model and to verify the distribution of these differences. The experiment’s histograms of the difference in the dependent variable are shown in Table 31. “If the samples contain more than 50 scores the sampling should be normally distributed” (Field, 2009, p. 327). In the third experiment, there is data for 490 repairables, each of which has 27 situations, and 13,203 samples. Field

(2009, p. 329) affirms, “use a big sample and [do] not worry about normality.” Based on Table 31 and the arguments previously identified here, the researcher can infer that the data are normally distributed.

Table 31. Histogram of difference—experiment 3.

Experiment 3—Difference IC



(2) Hypotheses Analysis

For the third experiment, hypothesis 4 was tested in which the researcher supported hypothesis 3 using recorded data. The result shows that on average, the experiment presents a predicted inventory cost that is significantly lower using the MERP model (M=2,098.25, SE=62.23) than the inventory costs from the EOQ/ROP model (M=7,595.14, SE=329.98), $t(13203)=18.31$, $p<.001$, $r=.16$. The researcher can reject the null hypothesis and conclude that the predicted inventory cost of the MERP is significantly lower than that of the EOQ/ROP model, and that it has a small effect. The experiment verifies that the conceptual simulation model done in experiment 2 can be repeated with real data. The results are shown in Table 32.

Table 32. Dependent *t*-test results.

	Exp. 3 - IC	
	MERP	**EOQ**
Mean	2,098.25	7,595.14
Std. error	62.23	329.98
mean diff	5,496.86	
N	13,203	
t	18.31	
sig	.000***	
r	0.16	

***p<0.001

4. Experiment 4—Response Time Experiment

Response time in this context is the capability to respond with efficiency and effectively to the abrupt variation in demand. When the model responds with low costs, the model has a satisfactory response time.

The goal of experiment 4 is to measure the response of each model when there is an abrupt variation of an independent variable. The experiment causes destabilization in the maintenance environment to measure the response of each model.

a. Experiment Design

The experiment uses the range independent variables presented in Table 33.

Table 33. Range of independent variables—experiment 4.

K	H	S	# U	Lt	MTBUR	Models
100%	30%	100%	225	30	25%	EOQ/ROP
15%	22%	50%		15	100%	MERP
5%	5%	20%	5	5	200%	

In this simulation, the last two years of the experiment are represented for a semester as in the following: "y.1," first half of the year "y", "y+1.2," second half of the year "y+1." To simulate the abrupt range, only the "# usage" will vary during the simulation. In each situation, the basic value of #U =125. The simulator will maintain the

base value of # usage of the situation in period y-2, y-1, y.1 and y+1.2, and will change y.2 and y+1.1 with respective values of the range (5–225). In Situation 1 Range (225), the simulator will change values as shown in Table 34.

Table 34. Example of parameters in the experiment 4.

Period	#Usage
y-2	125
y-1	125
y.1	125
y.2	**225**
y+1.1	**225**
y+1.2	125

The factorial design has 3^5 =243 situations (S) with two abrupt variations of #U (A), and 110 repetitions for each model. This represents 53,460 samples of each model from which to compare results.

$$S_1^{243} A_1^2 R_1^{110} \text{ ---------------X(EOQ)-----------------------O}$$
$$S_1^{243} A_1^2 R_1^{110} \text{ ---------------X(MERP)---------------------O}$$

b. Simulation

The simulation uses the same process as the first and second experiments.

c. Statistical Test

To compare the models, the study will test the hypothesis:

H_0 : MERP increases or keeps the same inventory costs compared to EOQ/ROP. $IC_{MERP} \geq IC_{EOQ/ROP}$

H_5 : MERP lowers inventory costs compared to EOQ/ROP. $IC_{MERP} < IC_{EOQ/ROP}$

To test this hypothesis, the study uses a dependent t-test (paired t-test) to compare the means of the inventory costs of both models.

d. Assumption of the Simulation

It is the same as in the second experiment.

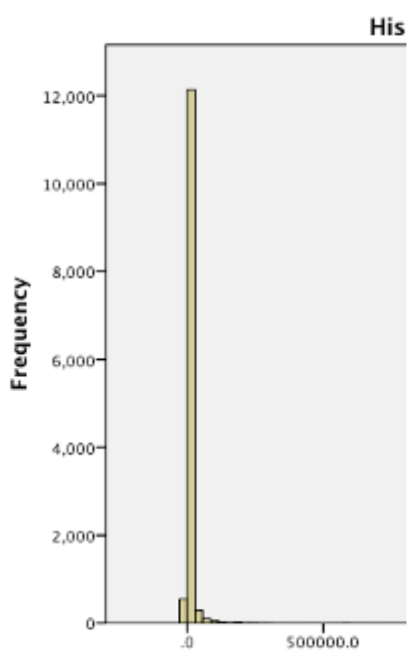
e. Result Analysis

To compare the models, the researcher discusses the dependent t-test assumption and the result of comparison.

(1) Statistical Assumptions Analysis

To check if the difference is normally distributed, the researcher calculates the difference between the inventory cost results of each model and to verify the distribution of these differences. The experiment's histograms of the difference in the dependent variable are shown in Table 35. According to Field (2009, p. 327), "if the samples contain more than 50 scores the sampling should be normally distributed." In experiment 4, there are 110 replications in each situation, and 53,460 samples of each dependent variable. Field (2009, p. 329) affirms, "use a big sample and [do] not worry about normality." Based on Table 35 and the arguments previously identified here, the researcher can infer that the data are normally distributed.

Table 35. Histogram of difference—experiment 4.

Experiment 4 - Difference IC


(2) Hypotheses Analysis

For the fourth experiment hypothesis 5 was tested, in which the researcher verified the response of the model with abrupt variation of maintenance demand during the experiment. Hypothesis 5 determines the inventory cost comparison in which the results show that on average, a predicted inventory cost is significantly lower using the MERP model (M=2,125.02, SE=6.35) than the predicted inventory costs of the EOQ/ROP model (M=36,795.72, SE=286.19), $t(53{,}459)=122.46$, $p<.001$, $r=.47$. The researcher can reject the null hypothesis and conclude that the inventory cost of the MERP is significantly lower than that of the EOQ/ROP model, and that it has a large effect. The experiment verifies that the MERP model can respond better to abrupt variation of demand. The result is shown in Table 36.

Table 36. Dependent *t*-test results experiment 4.

	Exp. 4 - IC	
	MERP	**EOQ**
Mean	2,125.02	36,795.72
Std. error	6.35	286.19
mean diff	34,670.70	
N	53,460	
t	122.46	
sig	.000***	
r	0.47	

***p<0.001

C. SUMMARY

This chapter presented the research results to support that the lateral and vertical information integration among the elements of the maintenance supply chain can decrease the level of uncertainty of this environment. Experiments 1–4 realized simulations that represented the maintenance environment of hypothetical aircraft repairables.

The first task of the simulation was to validate the relationship between the independent variables with the dependent variables. The validation was supported for the

F-ratio and t-test for coefficients with significantly results. Experiment 2 compared the inventory cost of the proposed MERP model with that of the traditional model used in many companies. This simulation sought to use the possible range of the independent variables to test different scenarios. The result showed that the MERP model could reduce the uncertainty and could produce lower cost.

To support the simulated result, experiment 3 used recorded data to test whether the experiment could be reproduced with actual data. The hypothesis was again supported and the inventory cost was lower using the MERP model than with the EOQ/ROP model. Next, the researcher tested both models with abrupt variation of demand to measure the response time. The results showed the MERP could react significantly better than the EOQ/ROP to abrupt variations in demand. The researcher concluded that integrating information in the maintenance supply chain would reduce uncertainty and improve inventory cost performance. The summary of the experiments 1–4 is shown in Table 37.

Table 37. Experiment summary.

Experiment	**Characteristic**	**Conclusion**	**Statistical Test**
Validation	Simulate low and high uncertainty to verify the validation of each model.	The results supported the validity of the models to simulate the data for simulation comparison.	ANOVA with F-ratio, Result: $p<.001$ B coefficients with *t*-test $p<.001$ Large effect size
Simulated Data	Simulate low and high uncertainty to verify the cost of each model.	With high uncertainty, MERP can connect the elements of supply chain reducing uncertainty and cost.	Dependent *t*-test, Result: $p<.001$ Large effect size

Experiment	Characteristic	Conclusion	Statistical Test
Recorded Data	With the same situation used in the empirical experiment, all situations were simulated with real data.	The simulation supports the simulated result. With actual data of demand, if inventory control uses the MERP model better inventory cost results than from the EOQ/ROP. This affirms that lateral and vertical integration increases the effectiveness of the system.	Dependent t-test, p<.001 Small effect size
Abrupt Variation	After the response of the system was supported in the simulated and actual data experiments, the researcher tested the model with abrupt variation of demand to verify the response.	In this environment of high uncertainty, the MERP showed performance much superior to that of the EOQ/Model. This supports the hypothesis that in an environment with high uncertainty, MERP models can have a better response.	Dependent t-test, p<.001 Large effect size

After the hypotheses were supported, the researcher was able to answer the following question: how does the integration of information affect uncertainty, and consequently, inventory performance in maintenance supply chain? When the elements of a maintenance supply chain are integrated, the level of uncertainty in that environment decreases, and, consequently, improves inventory performance.

Before concluding, it is salutary to explain about reliability and validity of the research. For the construct validity of the research, the author sought to operationalize the independent variables to represent all possible situations. The dependent variable measuring processes were mathematic and objective. In conclusion, the experiment measured what was required by the research.

For internal validation, the research used simulations that controlled all possible extraneous and confound variables in the experiments (i.e., these variables influenced the dependent and independent variables) (Johnson & Christensen, 2008, p. 253). The weakness of the simulation was the generalized hypothesis.

To compensate for this weakness, the research included an experiment with recorded data to support the simulated data of the other experiments. The recorded data was randomly chosen and drawn from a specific number of maintenance data from the Brazilian Air Force. For external validation, the research sought to use a wide range in the independent variables that represented almost all possible real situations. The sample size of each experiment was large enough to decrease the standard error of the means.

For the validity of the statistical conclusion, the researcher showed that there is a strong relationship between independent and dependent variables with a good magnitude of the relationship. The reliability of the experiment was supported by the repeatability of the results (Johnson & Christensen, 2008). The experiments, which were simulations with formulas that do not change, returned results that could be repeated systematically.

The results pointed to the conclusion that when the elements of a maintenance supply chain are integrated, the level of uncertainty in that environment decreases and, consequently, the inventory costs decreased.

V. CONCLUSION

This study sought to explore an information-processing theory and to analyze the effectiveness of information integration among the elements in the maintenance supply chain. This environment included components with stochastic failure rates, different types of failures needing repair, great numbers of spare parts needed for repairs, and long lead times to perform maintenance and to purchase spare parts. The demand for maintenance was hard to predict because "demand of repairs crops up unexpectedly and sporadically" (Cohen et al., 2006, p. 131). Without the integration and processing of information in a timely fashion, the level of uncertainty in the maintenance environment increases. While managers use techniques to mitigate the mismatch, these techniques often increase costs (Cohen et al., 2006, pp. 132–133).; therefore, the problem is that high uncertainty and the lack of integration of information cause inventory mismatch (excesses and shortages of spare parts).

This study used MRP techniques, system theory, and information-processing theory to develop a model that integrated lateral and vertical information to address the problem. The literature was inconclusive on the use of the Galbraith theory across the elements of a supply chain, as well as the use of MRP having a capacity to manage the uncertainty in the maintenance environment. This study sought to fill these gaps by answering the research question: does integrating information in the maintenance supply chain affect uncertainty and consequently, inventory cost?

The importance of this research was to bring a new framework to the maintenance supply chain. This sector generally uses traditional inventory models based on the historic consumption of material to plan the need for spare parts used in maintenance. To better predict the spare parts needed, the new model to plan maintenance is based on usage and the failure rates of the equipment and connects the elements of the supply chain. It is clear that if there is an integration of the information sources (customer, parts suppliers, warehouse, transportation), the supply chain will perform better. Yet there has been no previous study in the maintenance environment that has made such an investigation. This study, which was based on information-processing theory, makes a

valuable contribution to the maintenance field in examining how the integration of information affects the uncertainty, and consequently, the inventory cost.

To summarize the main points of the research, this chapter seeks to give to the reader a synthesis of the dissertation report starting with empirical findings and evidence that answered the research question. Following that, the author explains the theoretical contributions of the research (extends information-processing theory to the supply chain and theoretical foundation to MRP), and how the findings may affect practice in the maintenance supply chain in future. The author acknowledges some limitations of this study, and offers suggestions for future research. Finally, the author summarizes the significance and contribution of the dissertation.

A. RESEARCH METHODS AND FINDINGS

This study is a quantitative method research that studies the effect of the use of two models on inventory costs. The scenario comparison uses full-factorial simulation that consists of four experiments. The researcher developed two simulators; one represents the new model, and the other represents the traditional inventory control model. The design of the new model (MERP) was based on systems theory and information processing theory. The experimental procedure consisted of four experiments to test five hypotheses. The hypotheses test used the F-test and t-test to verify the significance of the findings.

Experiment 1 was designed to validate the relationships between the variables of each simulation model with the dependent variable. The results supported hypotheses 1 and 2 using the F-ratio and t-test. Both models have a significant ($p < .001$) degree of accuracy in predicting the inventory costs. Furthermore, the independent variables make a significant contribution ($p < .001$) to predicting inventory costs.

Once the models were validated, experiment 2 compared the inventory costs between the two models. The results showed that hypothesis 3 is supported. The dependent t-test supported that when MERP is used to manage inventory, the inventory cost is significantly ($p < .001$) lower than it is with EOQ/ROP models.

Experiment 3 verified whether the conceptual simulation model that was done in experiment 2 could be repeated with recorded data from the Brazilian Air Force. The test showed that hypothesis 4 was also supported by the dependent statistic t-test showing MERP inventory cost being significantly lower ($p<.001$) than that of EOQ/ROP. The results supported that the conceptual simulation models can be an accurate representation of the maintenance supply chain.

Experiment 4 observed the response of each model when there were abrupt variations of independent variables. Experiment 4 supported hypotheses 5, which implied that there was strong evidence ($p<.001$) of abrupt variations during maintenance that the MERP model decreased inventory costs when compared to the EOQ model.

In summary, the five hypotheses of the experiment were supported and the research affirmed that when information is integrated among the elements of the maintenance supply chain, uncertainty and inventory costs are reduced. It is necessary to explain why the phenomenon happens using logical reasoning to connect the conditions, theories, laws, and particular facts. Why does the MERP model produce better results if it uses the same formulas to calculate EOQ and safety stock? I will use the following theories to explain.

1. Explanation Using System Theory

The EOQ/ROP model that represents the traditional inventory control model does not integrate the information of the supply chain elements, and as the supply chain is a system, the relation between the elements is thus destroyed. In this case, feedback loops cannot be effective. To compensate for this weak feedback and increased level of uncertainty, the EOQ model uses more safety stock. Many times, though, because of the dynamic environment, the inventory model could not react quickly enough to the abrupt change in demand and the increased uncertainty, and by have more buffers than necessary it drove up the inventory costs. In other cases, the inadequate or untimely response of the traditional model resulted in a material shortage, causing high inventory costs.

When the MERP integrated the elements of the supply chain, this chain became a system. When the supply chain works like a unified system, the feedback mechanism can respond more effectively to any stimulus in the elements. The degree of separation between elements becomes lower, and then the information reaches the elements of the chain more quickly. Because of the fast reaction, the model can decrease uncertainty and, consequently, the inventory costs can decrease.

2. Explanation Using Information Processing Theory

As the EOQ/ROP model does not have the capability to process and connect information with other elements of the supply chain, this model tries to decrease uncertainty by increasing the buffers. EOQ models use information about the historic consumption and position of stock to calculate and suggest order decisions, but because it has limited information, the model increases the buffers to decrease the uncertainty. Doing that increases the cost of inventory. Moreover, this decision is not communicated quickly, if at all, with the other elements of the supply chain. Many times, when there are changes in demand or any change in the maintenance environment, the EOQ/ROP model cannot react quickly and effectively, resulting in shortages or excess inventory and causing high costs.

By contrast, the MERP model connects the elements of the maintenance supply chain, integrating lateral and vertical information. In this environment, when the fail rate of the equipment changes, this information can reach the elements of supply chain quickly. Then the demand can be recalculated and the supply chain can respond quickly. In other situations, such as when clients use the equipment more or less than planned, the model provides this information to the elements so that the whole system can react quickly to the variation. When there is an integration of information, the system can react to any change and process the information more quickly, reducing the uncertainty in this environment. This increased responsiveness is reflected in reduced inventory costs and stock amplitude.

B. THEORETICAL IMPLICATIONS

The proposed model brings a new framework to use in maintenance supply chain, and this research adds further knowledge to the field of information-processing theory. The study extends this theory to the supply chain environment, and brings new theoretical foundations to the MRP. Following are details of this contribution.

1. New Model for Maintenance Supply Chain

This research discussed and tested a new model for Maintenance Supply Chain. The result showed that this new model could increase inventory performance in this environment. The literature showed that an ERP system without customization tends to fail. This new models is ready to apply in the maintenance supply chain environment.

For the practitioners, the MERP model brings a new framework to the maintenance supply chain. Literature review shows scarce research about models that attend to this environment. For best performance, the ERP must be customized for the specific environment (Ernst & Cohen, 1993). This model brings a new management dimension to the maintenance supply chain. Using the MERP model, MRO organizations can integrate the elements of the maintenance supply chain. The model can integrate information from clients and suppliers, and can produce maintenance and purchase planning.

Many types of ERP software are concentrated to deliver products to the manufacturing area (Cohen et al., 2006). This research brings a software specification that can be used to develop new ERP software focused on the after-sales supply chain. This new area is the "longest-lasting source of revenue to companies," and requires special attention. Organizations that ignore the specificity of this area "do so at their own peril" (Cohen et al., 2006).

2. Extend Information Processing Theory to Supply Chain

When Galbraith formulated the information-processing theory in 1974, it was a different business environment. It was difficult for companies to establish good network connections, to process high volumes of information at high speed, or to acquire good

computers affordably. Many organizations had to work in isolation and without integrated systems. Galbraith's theory claims that if companies cannot increase information processing, they will construct their own mechanisms to decrease the uncertainty.

Galbraith's theory (1974, 1977) claims that if organizations integrate lateral information flow and increase vertical information flow, these companies can process more information and decrease uncertainty. He focused "on macro-organization variables, and on behavior at the level of the entire organization" (Levitt et al., 1999, p. 1483). Levitt et al. (1999, 2005) extended the information-processing theory using quantitative research to a micro-contingency model of organizational behaviors.

This research extends the use of the information-processing theory to the elements of supply chain management by creating a model that integrates information within and across the supply chain proving a performance increase in the supply chain. Because of the complexity of the maintenance environment, the model organizes, shares, and integrates information among the elements of the maintenance supply chain (e.g., users, organization, suppliers). The MERP framework increases the integration capability, and consequently, can increase supply chain performance.

This research has operationalized a quantitative research with a simulation that integrates lateral and vertical information among the elements of the maintenance supply chain. This simulation can capture the reaction of the stimulus in each supply chain element and measure the result. With this simulation, models can produce comparable performance results that help to understand the effect of uncertainty with and without an information-processing theory; therefore, the research permits the exploration of complex situations in the supply chain.

The model extends the Galbraith (1974, 1977) theory to supply chain elements by increasing the lateral and vertical integration of information flow, providing a simulation that permits measuring the effect of information integration in the supply chain.

3. Theoretical Foundation to MRP Model

According to Ptak and Smith, "When MRP started, academics considered the study of MRP vocational rather than scientific (2011, p. 375). Many academics have tried to use sophisticated mathematical formulas to formulate MRP theories (Grubbström et al., 2010; Kovačić & Bogataj, 2010), but they had difficulty creating a single theory and explanation. The model is simple; it integrates the demand with planning information, and then with purchase and manufacture orders. Finally, it gets information from production and suppliers to make decisions.

This research created models using the techniques of MRP models. The explanation that was used to understand why the integration increased the performance of MRP models could be used to support the MRP models themselves. An MRP model is a simple technique that integrates lateral and vertical information to make decisions. The information-processing theory claims that when companies integrate lateral and vertical information, they reduce the uncertainty and increase the performance, which is what MRP is doing.

This research supported this argument with quantitative results showing what happens when companies do not integrate information and use static models such as EOQ/ROP. The research compares these results to those when organizations apply lateral and vertical integration to reduce uncertainty. This research enabled the exploration of a complex supply chain comparing traditional models with integrated functions that use MRP techniques.

C. LIMITATIONS AND RECOMMENDATIONS

The supply chain is a new area that arose in only a few years. The globalization and connection among the elements of the supply chain brought new challenges. This research supports the view that with information integration, using principles of information processing theory, the supply chain has better performance.

As to the limitations of this research, we will discuss the simulation and quantitative results. A simulation tries to represent a real situation using all possible representations and modeling, but it is difficult to represent all objects and relationships,

particularly in the maintenance environment. The research focused on uncertainty in maintenance and spare part demands; however, the reality was even more complicated. External but important to this environment, are other elements that are difficult to predict or control, such as delivery times from suppliers and to clients, and maintenance times. It is recommended that a simulation be performed using these others elements.

This research performed information integration and experiments with one repairable of an aircraft, with a client, and a supplier. The reality of the supply chain is that thousands of items, as well hundreds of suppliers and clients, are involved. The author suggests that an experiment be performed using a high number of elements in the supply chain (more suppliers, more repairables, more clients), and with uncertainty among the elements to simulate a dynamic environment and the effect of others supply chain. The idea is to measure the performance of the model in this complex environment.

The author suggests the use of the new model in a tactical environment where the model can be tested with dynamic situations and decisions. This model could help the decision maker to focus on challenges in the tactical environment, based on spare part predictions and expected hours of operation and failure rate. With this model, the environment could respond quickly to new events that often happen during tactical decisions.

The author believes that the key to the supply chain is simulation. Many researches emphasize mathematical tractability and significance; however, in a dynamic environment, static results do not always work. Thus, for the supply chain, studies using simulations models should be considered for the future. As guidance for this future work, this researcher offers, "more empirical modeling that includes forecast error and less reliance on spurious mathematical simplicity is required" (Fildes & Kingsman, 2011).

D. SUMMARY

The research addressed the integration of information in the maintenance supply chain to reduce uncertainty and inventory costs. The research used simulations to represent two models: 1) a model that does not connect information and uses buffers to reduce uncertainty, represented by the EOQ/ROP model; and 2) another model that

connects lateral and vertical information to increase the information processing and reduce uncertainty, represented by the MERP model. The quantitative research tested five hypotheses to answer the research question, which are summarized in Table 38.

Table 38. Hypotheses summary tested.

Hypothesis	Goals	Significance	Effect size	Test	Assessment
Hypothesis 1. The EOQ/ROP and MERP Model predict significantly (0.05%) well the inventory cost	Validation of the model. (Internal Validation)	p<.001	Large	F-test	Supported
Hypothesis 2. β contribution affects the inventory cost (different from zero)	Validation of the model (Internal Validation)	p<.001	Large	t-test	Supported
Hypothesis 3. MERP lowers inventory cost compared to EOQ/ROP	Det'm which model results in lower inventory costs with simulated data	p<.001	Small	t-test	Supported
Hypothesis 4. MERP lowers inventory cost compared to EOQ/ROP	Validate the result of Exp. 2 with recorded data (Generalization)	p<.001	Large	t-test	Supported
Hypothesis 5. MERP lowers inventory cost compared to EOQ/ROP	Det'm which model is more responsive to abrupt variation in system	p<.001	Large	t-test	Supported

After the hypotheses were supported, the following research question was answered: how does the integration of information affect uncertainty, and consequently, inventory performance in maintenance supply chain? When the elements of a maintenance supply chain are integrated, the level of uncertainty in that environment decreases, and, consequently, improves inventory performance.

After answering the research question, it was shown that the information integration could transform the elements of a supply chain to work as a system, and bring better results and advantages to an uncertain environment. Information integration does reduce uncertainty and inventory costs.

This research extended Galbraith's theory to the supply chain. This research specifically extended the use of the information-processing theory to supply chain elements, showing that lateral and vertical integration of information can decrease uncertainty and improve performance in the supply chain. Therefore, the research permitted the exploration of complex situations in supply chains.

This research brought a new theoretical foundation to MRP. The MRP model connects lateral and vertical information, which is a principle of the information-processing theory; therefore, the information-processing theory can be a theoretical foundation to explain MRP models.

Next, this model brought a new framework to the maintenance supply chain. Specifically, this model brought a new management dimension to the maintenance supply chain. Using the new model, MRO organizations can develop a customized ERP to attend to the complex environment and decrease uncertainty and inventory costs. This framework fits well in organizations that specialize in maintenance management and service supply chains.

Finally, this research provided new approaches to the study of information sciences and supply chains. This author affirms that integration of information in the maintenance supply chain reduces uncertainty and inventory costs. The reality is that companies have the power to process a high volume of information with high-speed networks. The new challenge is how to organize and integrate this information to increase a company's overall performance. Information sciences that study the relationships of information can provide an important contribution to this new field.

APPENDIX A. VISUAL BASIC CODE

EXPERIMENTS 1 AND 2

```
Sub First_second_experiment()

' Calculate1_2EXP
'
' Keyboard Shortcut: Option+Cmd+1
'
    'cleaning

    Sheets("MRP EOQ Result").Select
    Range("A1:W81000").Select
    Range("W81000").Activate
    Application.CutCopyMode = False
    Selection.ClearContents
    ActiveWindow.ScrollRow = 1
    Range("A1").Select

    'change parameters


    ArraySum = 0
    For j = 8 To 736
    ArraySum = ArraySum + j
    Sheets("Planning").Select
    Range("C" & j & ":" & "H" & j).Select
    Range("H" & j).Activate
Selection.Copy
'copy first data

'paste

Sheets("Change Parameters").Select
    Range("G28").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False

' EOQ and MRP Result copy result

    ArraySum = 0
    For i = 1 To 110
    ArraySum = ArraySum + i
```

```
    Calculate
    Sheets("Results").Select
    Range("A2:W2").Copy

    'next empty cell and paste

    Sheets("MRP EOQ Result").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
    Selection.Offset(1, 0).Select

Next i


Next j



End Sub
```

EXPERIMENT 3

```
Sub Calculatedatareal()
'
' Calculate cost with real data
'
'delete old result

    Sheets("Result_final").Select
    Cells.Select
    Selection.ClearContents

    ArraySum = 0
    For I = 1 To 90
    ArraySum = ArraySum + I
    Sheets("PN").Select

'copy first data
Range("A" & I).Select
      Selection.Copy

'paste

    Sheets("Parameters OS").Select
```

```
    Range("C3").Select
    ActiveSheet.Paste
    ActiveSheet.Paste
    Application.CutCopyMode = False

ArraySum = 0
    For j = 8 To 34
    ArraySum = ArraySum + j
    Sheets("Planning").Select
     Range("B" & j & ":" & "H" & j).Select
    Range("H" & j).Activate
Selection.Copy
'copy parameters

'paste

Sheets("Cost_Parameters").Select
    Range("G16").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False

  Calculate

'copy result

    Sheets("Result_1").Select
    Range("A1:H1").Select
    Selection.Copy

'record result

    Sheets("Result_final").Select

    'next empty cell in the column and paste

    lMaxRows = Cells(Rows.Count, "A").End(xlUp).Row
    Range("A" & lMaxRows + 1).Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

     Next j

   Next I

End Sub
```

EXPERIMENT 4

```
Sub Fourt_experiment()

' Calculatefourth
'
' Keyboard Shortcut: Option+Cmd+4
'
'cleaning old result

    Sheets("MRP EOQ Result").Select
    Range("A1:AB80000").Select
    Range("AB80000").Activate
    Application.CutCopyMode = False
    Selection.ClearContents
    ActiveWindow.ScrollRow = 1
    Range("A1").Select

   'change parameters
    ArraySum = 0
    For j = 8 To 493
    ArraySum = ArraySum + j
    Sheets("Planning").Select
    Range("B" & j & ":" & "H" & j).Select
    Range("H" & j).Activate
Selection.Copy
'copy first data

'paste

Sheets("Change Parameters").Select
    Range("F30").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False

' EOQ and MRP Result copy result

    ArraySum = 0
    For i = 1 To 110
    ArraySum = ArraySum + i
    Calculate
    Sheets("Results").Select
    Range("A2:AB2").Copy

    'next empty and paste
```

```
    Sheets("MRP EOQ Result").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
    Selection.Offset(1, 0).Select

Next i


Next j



End Sub
```

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APPENDIX B. ALGORITHMS

RANDOM POISSON

```
Function MBA(lambda As Double) As Long
Static dblOld As Double, g As Double
Dim ret As Long, t As Double
Application.Volatile
If lambda <> dblOld Then
dblOld = lambda
g = Exp(-lambda)
End If
ret = -1
t = 1#
Do
ret = ret + 1
t = t * Rnd()
Loop While t > g
MBA = ret
End Function
```

INVERSE POISSON

```
Function poisson_inverse(p, lambda)
' p is culambdalative probability
' lambda is mean of the Poisson distribution
' This routine truncates the result at xmax

Dim x As Integer
If lambda > 60 Then
x = Round(WorksheetFunction.NormInv(p, lambda, Sqr(lambda)), 0)
poisson_inverse = x
Else
Const xmax = 100
For x = 0 To xmax
poisson_inverse = x
If Application.WorksheetFunction.Poisson(x, lambda, True) >= p Then Exit Function
Next x
MsgBox "poisson_inverse(" & Format(p, "0.00 percent") & ") was truncated at " &
Val(xmax) & ".", vbExclamation

End If
End Function
```

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APPENDIX C. BRAZILIAN AIR FORCE DATA

AIRCRAFT CODES

Table 39. Aircrafts Sample from Brazilian Air Force.

Aircraft Code	Acronym	Description
A3	C-130	LOCKHEED C-130 HERCULES
A7	C-95	EMB-110 BANDEIRANTE
C7	KC-137	BOEING 707-320C
F4	A-1	AMX
F5	F-5	NORTHROP F-5E E F-5B TIGER II
H2	H-50	ESQUILO MONO-REATOR
H5	H-34	SUPER PUMA 332M
R1	R-35A	LEARJET 35 E 55
S2	H-1H	BELL UH-1 IROQUOIS
T1	T-27	TUCANO
T2	A-29	AL-X SUPER TUCANO A-29A/A-29B
T9	T-25	NEIVA T-25 UNIVERSAL

REAL DATA SUMARY

Table 40. Data sample from Brazilian Air Force.

PN	CFF	NAME	AIRCRAFT	QTY_WO	PN SPARE PART	CFF SPARE	NAME SPARE	USD
035262-01	90005	FILTER ASSEMBLY	F5	9	034929	99207	PACKING,PREFOR	0.34
1-080-250-25	99193	CAIXA DE ENGRENAGEM, MOTOR ACESSÓRIO, MOTOR DA TURBINA	S2	11	1-300-232-02	04795	SEAL,PLAIN ENC	14
103D100	99193	CAIXA DE ENGRENAGEM, MOTOR ACESSÓRIO, MOTOR DA TURBINA	S2	11	1-300-232-02	04795	SEAL,PLAIN ENC	14
103D100-1	17472	ACTUATOR,ELECTRO-MECHANICAL,ROTARY	F5	7	103A300-1	17472	PARTS KIT,OVERHAUL	561.05
107C950-2	78711	MICROPHONE	A3	5	107D411-1	78711	MICROPHONE	126.461
1333-613233M1	09523	VALVE	A3	17	1433-623304	09523	ACTUATOR,ELECTRO-MECHANICAL,ROTARY	11445.259
14-13901-3	76823	CONNECTING LINK	F5	2	GB525A5	77896	BEARING,ROLLER,ROD END	181.14
14-17030-503-C	76823	KIT CONVERSION PYLO	F5	4	AV24B1125C	73760	VALVE	252.4
14-24301-501	76823	DOOR MLG	F5	10	51B234-3	0JRC1	SCREW,CAP,SOCKET HEAD	6.71
14-41650-1	76823	DRAG BRACE,LANDING GEAR	F5	6	NAS561CF5-24	80205	PIN,SPRING	0.58
14-43270-1	76823	CYLINDER ASSEMBLY	F5	19	LMT-12915	00288	TRANSDUCER,MOTIONAL PICKUP	1539.25
14-82003-505-C	76823	LAUNCHER GUIDE LH	F5	3	14-82025-3	76823	COVER ASSY LH	2115.951
180-147	63367	JUG,INSULATED	A3	12	B5377	63367	GASKET	84.32
2-43140-502	76823	CYLINDER ASSEMBLY	F5	30	MS28782-19	96906	RING TEFLON	6.16
2-43330-512	60029	SERVOCYLINDER, ACTUATOR, RUDDER RH	F5	16	SM5-8C-12	77896	BEARING,ROLLER,ROD END	248.43
223585	79318	FUEL HEATER VALVE	C7	14	155150-2	79318	ACTUATOR	2490
23081-012	31435	GERADOR DE AERONAVE	A7	6	M2030AC-2	18783	BEARING,BALL,ANNULARL	85.05
2317100-12	24210	ACTUATOR ASSY - NOSE GEAR	R1	5	2391700-1	24210	KIT NOSE GEAR	14.9
2401-	001J	MAIN WHEEL ASSY	F4	15	TR762-03	9715	VALVE,PNEUMAT	10.83

PN	CFF	NAME	AIRCRAFT	QTY_WO	PN SPARE PART	CFF SPARE	NAME SPARE	USD
0001-005	K					3	IC TIRE	
247-11	13539	CONTROL,LANDING GEAR	F5	10	247039	13539	KNOB C	418.37
2524440-5	07213	FCU	A7	18	SSR-4ZRA5P58LY17P	06848	BEARING	10
2524440-6	07213	FCU	A7	21	SSR-4ZRA5P58LY17P-1	06848	BEARING	10
25730043-03	45153	VALVE	A3	8	328419	77445	PACKING	0.16
2586333-1	07187	GYROSCOPE C-12	R1	5	875863	07187	TEAR BAND	15.45
2B7-38	26433	PUMP,SUBMERGED,AIRCRAFT	T1	38	2B7-38-MOTOR-ELETRICO	26433	PUMP,SUBMERGED,AIRCRAFT	2139.393
3-1587	97153	NOSE WHEEL ASSY 18X5.5	T2	24	13621	60038	CUP,TAPERED RO	8.801
30-1617-1	72914	LUZ ANTI-COL E	T1	9	31-3078-17-1	72914	FLASHTUBE ASSEMBLY	2365
30-1617-2	72914	LUZ ANTI-COL D	T1	18	31-3078-17	72914	FLASHTUBE ASSEMBLY	2365
3014704	73030	VALVE HOUSING ASSEMBLY,PROPELLER	A3	5	542185	73030	RESISTOR,VARIABLE,WIRE WOUND,PRECISION	176.259
30700-00001	005HK	CONTROL V/VHF	F4	10	KW105S	58774	INDICATOR, DIGITAL DISPLAY	164.868
3070300-11	99193	ENGINE MODEL TFE731-2-2B	R1	12	MS9581-09	96906	WASHER	9.166
3070300-12	99193	ENGINE MODEL TFE731-2-2B	R1	8	525-618-9002	99193	NUT	0.819
3070300-9	99193	ENGINE MODEL TFE731-2-2B	R1	20	S9413-013	99193	O-RING	3.38
30B107-19-A	83298	GERADOR DE AERONAVE	R1	32	M1030BX-1	18783	BEARING, BALL	247.68
3104279-01	00198	HOUSING	A7	8	3104278-01	00198	COVER ASSEMBLY	986.48
3201KGA/CP/1	K5294	TACHOMETER	A7	31	BCP1721	K0481	BEARING	1131.292
3213722-5-1	99193	VALVE, BLEED AIR	A3	4	880500-1	99193	PACKING,PREFORMED	12.26
332A33-0030-05	F0210	PUNHO RC	H5	3	704A33-651-069	F0210	BATERIE DE ROULAMENT	2487.041
370750-1	98897	CYLINDER, RAMP ACTUATING	A3	14	370752-1	98897	HEAD,RAMP CYLINDER	817.15
373531-7	98897	VALVE, NLG STEERING	A3	6	MS28775-012	98897	PACKING,PREFOR	0.081
374455-7	98897	BOOSTER, AILERON	A3	8	MS28775-222	96906	O-RING	6.49
376190-77	98897	POWER PLANT ASSY T56A15	A3	45	ST104A	61349	TRANSMITTER	7897.881

PN	CFF	NAME	AIR CRA FT	QTY _WO	PN SPARE PART	CFF SPA RE	NAME SPARE	USD
383198-1-2	99193	STARTER,ENGINE,AIRTURBINE	A3	14	357166	59364	SHAFT	1623.143
383198-1-4	99193	STARTER,ENGINE,AIRTURBINE	A3	10	357182	59364	BODY, GOVERNOR PARTS	6295.95
4-43200-509	76823	SERVOCYLINDER	F5	24	9835301-10	98748	KIT,ACTUATOR,CURE DATE	75.84
40070-21S7079	72914	LIGHT NAVIGATIONAL	F5	28	M6363/1-1	81349	LAMP,INCANDESCENT	11.08
4023400-0503	24384	TRANSCEIVER	F5	18	2073404-0705	06845	POWER SUPPLY ASSY	3076.101
499-00-3	09445	ACTUATOR, ELECTRO-MECHANICAL, DOOR,GROUND COOLING,100A/115V,0.03HP, 400 HERTZ,STEEL/PO	F5	21	299-08	09445	GEAR,SPUR	793.98
499-00-3-1	8T729	ACTUATOR, ELECTRO-MECHANICAL , DOOR,GROUND COOLING,100A/115V,0.03HP, 400 HERTZ,STEEL/PO	F5	19	299-10	09445	GEAR,SPUR	1599.76
501-1204-01	25583	VERTICAL GYRO	R1	12	561-1601-02	25583	SWITCH, MERCURY	43.584
50230-1	1ZAW4	VALVE,BUTTERFLY	F5	12	502306	26101	BEARING,SLEEVE	141.47
524-031	F0296	GERADOR DE AERONAVE	H2	19	408764B	F0296	BRUSH	260.54
540538-2-1	70210	ACTUATOR	A3	21	36726-1	70210	MOTOR	21634.615
55-8-1	54395	MOTOR COMPRESOR	R1	11	55-14-3003	54395	BRUSH ELECTRIC	145.651
5502636-2	98079	AMPLIFIER, ELETRONIC, CONTROL	A3	19	183997	32669	RELAY,ELECTRO MAGNETIC	1445.48
572880	73030	VALVE HOUSING ASSEMBLY,PROPELLER	A3	5	542185	73030	RESISTOR,VARIABLE,WIRE WOUND,PRECISION	176.259
6-73105-25	76823	MECHANISM ASSY	F5	4	51B333-13	0JRC1	SCREW,CLOSE TOLERANCE	6.455
60-2799-1	72914	POWER SUPPLY	T1	16	55-0834-641L2D2	72914	CAPACITOR,FIXED,ELECTROLYTIC	24.116
60-371C	81982	PUMP FUEL	A3	20	90-187	81982	VALVE ASSY, BY PASS	899.64
60-551	81982	PUMP DRAIN	A3	13	78-101	81982	MOTOR ASSY	4096
6007T92G01	99207	ENGINE J85GE21	F5	135	299C413P4	99207	O-RING	0.29
681D100-7	72121	ACTUATOR,ELECTRO-MECHANICAL,LINE	T1	14	SA13301	17472	SEAL	110.9
695568-1	98897	CYLINDER, NLG STEERI	A3	13	MS28775-222-1	96906	O-RING	6.49
6U6036	94641	VALVE,LINEAR,DIRECTIONAL CONTROL	F5	8	MS28774-017	96906	RETAINER,PACKI	0.01
733872-2	73030	HOUSING ASSY,PUMP	A3	33	69483C103-5880	73030	ANEL DE VEDAÇÃO	9.34

PN	CFF	NAME	AIR CRAFT	QTY_WO	PN SPARE PART	CFF SPARE	NAME SPARE	USD
753400-5	73030	REFRIGERATION PACKING	F5	16	69494J910	73030	O-RING	1.61
8210-003	66503	GOVERNOR,FUEL CONTROL	A7	19	3054-729	66503	GASKET	13.79
83120-2-1	70210	SEPARATOR	A3	5	500017	0BX85	STRAINER ELEMENT,SEDIMENT	32.68
836525-3A	98571	COMPONENT ASSY,STABILITY	F5	12	837298	98571	TRANSFORMER,POWER	984.63
836525-5	98571	COMPONENT ASSY,STABILITY	F5	5	1N645	81349	SEMICONDUCTOR	2.75
8TJ51GAA5	97424	POWER SUPPLY	A3	54	B5870	73693	GEARCASE-MOTOR	8800
9560569	01297	BREAK ASSY	C7	57	9525856	73842	PACKING	6.1
9560685	73842	BRAKE,MULTIPLE	A3	83	313010	21849	DISC,BRAKE	386.39
AL1020M4	12511	ACTUATOR,ELECTRO-MECHANICAL,LINEAR	F5	37	AA2512	12511	BEARING,BALL,ROD END	787.61
AL1020M5	12511	ACTUATOR	F5	15	AA2512-1	12511	BEARING,BALL,ROD END	787.61
B-140BH	74063	RELAY,ELECTROMAGNETIC	F5	17	K0-057	74063	RELAY KIT	2846.631
B123J	74063	CONTACTOR	A3	10	NK503-8-6	02615	SCREW SELF	0.15
B5A10001SKD	24692	PROPELLER ASSY	T2	41	4H3064-1	24692	DEICE BOOT	170.33
C7041-2	00268	ACTUATOR, RUDDER	A3	11	8504M1	00268	TRANSMITTER,PO	1332.859
D7080A24	72914	LIGHT,NAVIGATIONAL,AIRCRAFT	T9	50	5005-33-10-5W	AI76$	RESISTOR FIO	0.68
HSI PT6A-34	00198	KIT HSI	A7	26	3009024	00198	BOLT,SHAFT,COMPRESS	135.417
JG402A2	94580	INDICATOR	A3	20	450887-7	94580	CASE INDICATOR	294.81
JG402A3	94580	INDICATOR	A3	17	450887-7-1	94580	CASE INDICATOR	294.81
JG402A4	94580	INDICATOR	A3	16	450887-7-2	94580	CASE INDICATOR	294.81
MBEU116008	U1604	FRONT EJECTION SEAT - MKBR10LCX-1	T2	45	MBEU91171	F0754	WEBBING,ASSEMBLY	238.25
MBEU116009	U1604	REAR EJECTION SEAT - MKBR10LCX-2	T2	46	MBEU61512	U1604	PACKING	1.5
MBEU116029	U1604	EJECTION SEAT - MKBR10LCX	T2	33	MBEU36041	U1604	ANCHOR PIN ASSEMBLY	33.42
MBEU92941	U1604	ACTUATOR,ELECTRO-MECHANICAL,LINEAR	F4	16	MBEU90227	U1604	SEAL,RUBBER SPECIAL SHAPED SECTION	205.994
MBEU92941-1	U1604	ACTUATOR,ELECTRO-MECHANICAL,LINEAR	T2	37	MBEU60272	U1604	PLOCKET AND CABLE A	401.28
RFN3934	00198	CONJUNTO T5	A7	44	3040110	00198	WIRING HARNESS OPTION	1687.253

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APPENDIX D. EXPERIMENT RESULTS

SAMPLE RESULTS OF EXPERIMENTS 1 AND 2

Table 41. Sample result of experiments 1 and 2.

K	H	S	# Usage	LT	MTBUR	IC MERP	IC EOQ/ROP	EOQ-MERP IC
20	0.016	20	225.00	30.00	750	7,829.88	56,477.43	48,647.55
20	0.016	20	225	30	750	7,781.46	50,434.69	42,653.23
20	0.016	20	225	30	750	7,914.63	14,702.36	6,787.73
20	0.016	20	225	30	750	7,680.79	13,862.73	6,181.94
20	0.016	20	225	30	750	7,734.70	36,960.63	29,225.93
20	0.016	20	225	30	750	7,722.59	18,409.50	10,686.91
20	0.016	20	225	30	750	7,832.48	30,543.30	22,710.81
20	0.016	20	225	30	750	7,961.94	75,402.23	67,440.29
20	0.016	20	225	30	750	7,701.74	21,965.01	14,263.27
20	0.016	20	225	30	750	7,919.00	18,085.03	10,166.03
20	0.016	20	225	30	750	7,839.63	20,416.03	12,576.40
20	0.016	20	225	30	750	7,979.45	30,362.49	22,383.04
20	0.016	20	225	30	750	8,032.16	22,464.96	14,432.80
20	0.016	20	225	30	750	8,023.	52,079.04	44,055.08

K	H	S	# Usage	LT	MTBUR	IC MERP	IC EOQ/ROP	EOQ-MERP IC
						96		
20	0.016	20	225	30	750	8,634.38	47,592.44	38,958.06
20	0.016	20	225	30	750	7,839.43	14,589.29	6,749.87
20	0.016	20	225	30	750	7,985.34	27,935.10	19,949.76
20	0.016	20	225	30	750	9,924.78	44,999.75	35,074.97
20	0.016	20	225	30	750	7,930.00	14,098.51	6,168.51
20	0.016	20	225	30	750	8,038.43	27,555.80	19,517.37
20	0.016	20	225	30	750	8,113.26	51,731.85	43,618.60
20	0.016	20	225	30	750	7,702.32	40,264.70	32,562.38
20	0.016	20	225	30	750	8,907.91	27,765.80	18,857.89
20	0.016	20	225	30	750	11,726.86	50,969.90	39,243.04
20	0.016	20	225	30	750	7,833.56	33,122.11	25,288.55
20	0.016	20	225	30	750	7,983.36	33,648.09	25,664.73
20	0.016	20	225	30	750	8,001.81	46,350.92	38,349.11
20	0.016	20	225	30	750	9,390.76	31,803.85	22,413.09

SAMPLE RESULTS OF EXPERIMENT 3

Table 42. Sample result of experiment 3.

K	H	S	IC MERP	IC EOQ/ROP	EOQ-MERP IC
561.05	3.24	561.05	6,572.43	3857.31	2,715.11
561.05	3.24	280.53	6,572.43	3814.65	2,757.77
561.05	3.24	112.21	6,572.43	3789.05	2,783.37
561.05	2.37	561.05	5,348.53	4201.02	1,147.51
561.05	2.37	280.53	5,348.53	3835.166	1,513.37
561.05	2.37	112.21	5,348.53	3615.64	1,732.88
561.05	0.54	561.05	2,740.07	1976.36	763.71
561.05	0.54	280.53	2,740.07	1933.69	806.38
561.05	0.54	112.21	2,740.07	1908.09	831.98
84.16	3.24	561.05	2,855.47	2290.30	565.16
84.16	3.24	280.53	2,855.47	1839.11	1,016.35
84.16	3.24	112.21	2,855.47	1568.39	1,287.07
84.16	2.37	561.05	2,262.97	1374.38	888.59
84.16	2.37	280.53	2,262.97	1331.71	931.26

SAMPLE RESULTS OF EXPERIMENT 4

Table 43. Sample result of experiment 4.

K	H	S	Usage	LT	MTBUR	MERP IC	EOQ IC	EOQ-MERP IC
20	0.02	20	225	30	750	6840.30	356651.97	349811.67
20	0.02	20	225	30	750	6818.25	271089.12	264270.87
20	0.02	20	225	30	750	6793.99	286572.46	279778.47
20	0.02	20	225	30	750	6869.17	264474.36	257605.19
20	0.02	20	225	30	750	6941.61	243200.55	236258.94
20	0.02	20	225	30	750	6730.93	323619.25	316888.32
20	0.02	20	225	30	750	6752.89	118432.95	111680.06
20	0.02	20	225	30	750	6809.86	112742.67	105932.81
20	0.02	20	225	30	750	6770.25	294721.42	287951.17
20	0.02	20	225	30	750	6825.74	274987.21	268161.47
20	0.02	20	225	30	750	6740.97	178447.66	171706.69
20	0.02	20	225	30	750	6755.91	167228.45	160472.54
20	0.02	20	225	30	750	7949.11	231439.40	223490.30
20	0.02	20	225	30	750	6813.73	162162.16	155348.43
20	0.02	20	225	30	750	6730.83	238628.13	231897.30
20	0.02	20	225	30	750	6770.34	168257.90	161487.56
20	0.02	20	225	30	750	6737.56	177056.53	170318.97
20	0.02	20	225	30	750	6764.66	267854.63	261089.97
20	0.02	20	225	30	750	6658.67	244859.87	238201.20
20	0.02	20	225	30	750	6756.41	199074.09	192317.68
20	0.02	20	225	30	750	6887.72	212131.93	205244.20
20	0.02	20	225	30	750	6775.98	203802.93	197026.95
20	0.02	20	225	30	750	6795.52	235136.90	228341.38
20	0.02	20	225	30	750	6846.43	273400.61	266554.17
20	0.02	20	225	30	750	6802.06	286848.10	280046.04
20	0.02	20	225	30	750	6910.75	272907.96	265997.21
20	0.02	20	225	30	750	6854.64	317879.25	311024.61
20	0.02	20	225	30	750	6743.58	365665.73	358922.15
20	0.02	20	225	30	750	6842.03	197567.97	190725.94

APPENDIX E. SIMULATION OVERVIEW

SIMULATION MENU

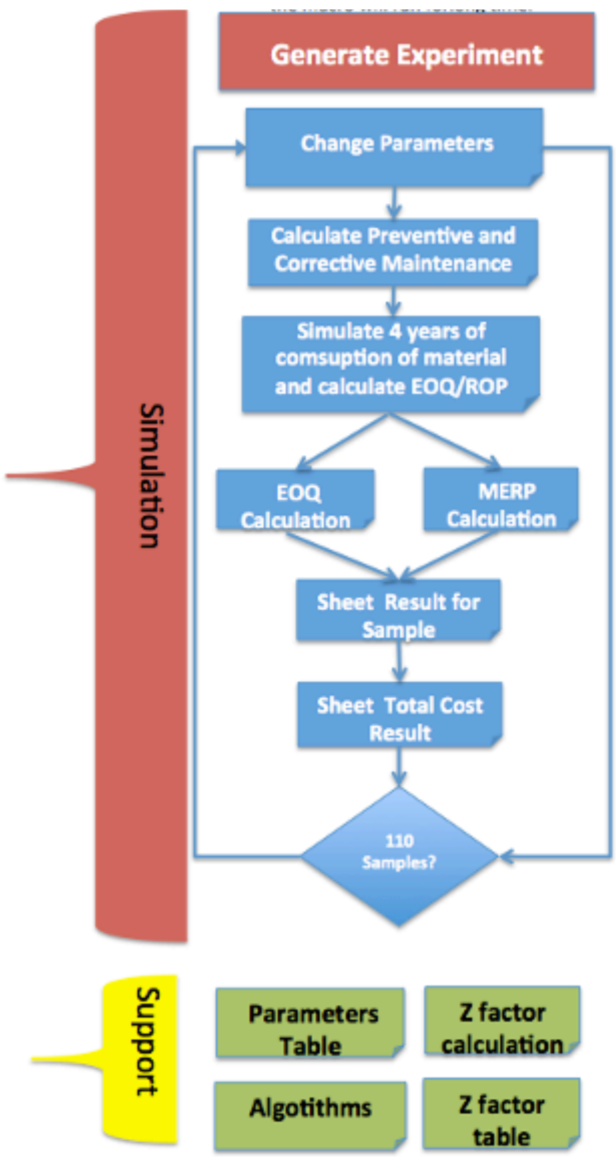


Figure 14. Front-end of the simulation.

Table 44. Parameter screen.

Parameters Changing

	Utilization per Month	MTBUR	TBO	QPA	# Aircraft
	k	λ	z	x	y
y-2	5	6000	3000	2	300
y-1	5	6000	3000	2	300
y	5	6000	3000	2	300
y+1	5	6000	3000	2	300

EOQ
MRP

Menu

		?
Cost Replacem	K	1.00
Price	v	20
rate	r a.a	5.000%
	r a.d	0.0137%
H=r*v	H-annual	$ 1.0000
	H-daily	$ 0.0027
Shortage	S	$ 4.0000
LeadTime	LT	5

Generate Experiment

			Value of Indepednent variable in the simulation					
Annual rate	5.0000%							
A.m	0.4167%		K	H	S	# Usage	LT (dias)	MTBUR (xTBO)
A.w	0.0962%		5%	5%	20%	5	5	200%
A.d	0.0137%		1.00	0.00273973	4	5.00	5.00	6000

Price	20					
	K	H	S	# Usage	Lt	MTBF
	100%	30%	100%	225	30	25%
	15%	22%	50%	125	15	100%
	5%	5%	20%	5	5	200%

Maintenace					
Material used	PN	Description	Value	Qtd	% Troca
	A	Screw	20	10	1
	B	Screw 2	25	20	0.8
	C	Arruela	30	25	1

Maintenace					
Material used	PN	Description	Value		% Troca
	A	Screw	20	10	0.8
	B	Screw 2	25	15	0.8
	C	Arruela	30	20	1

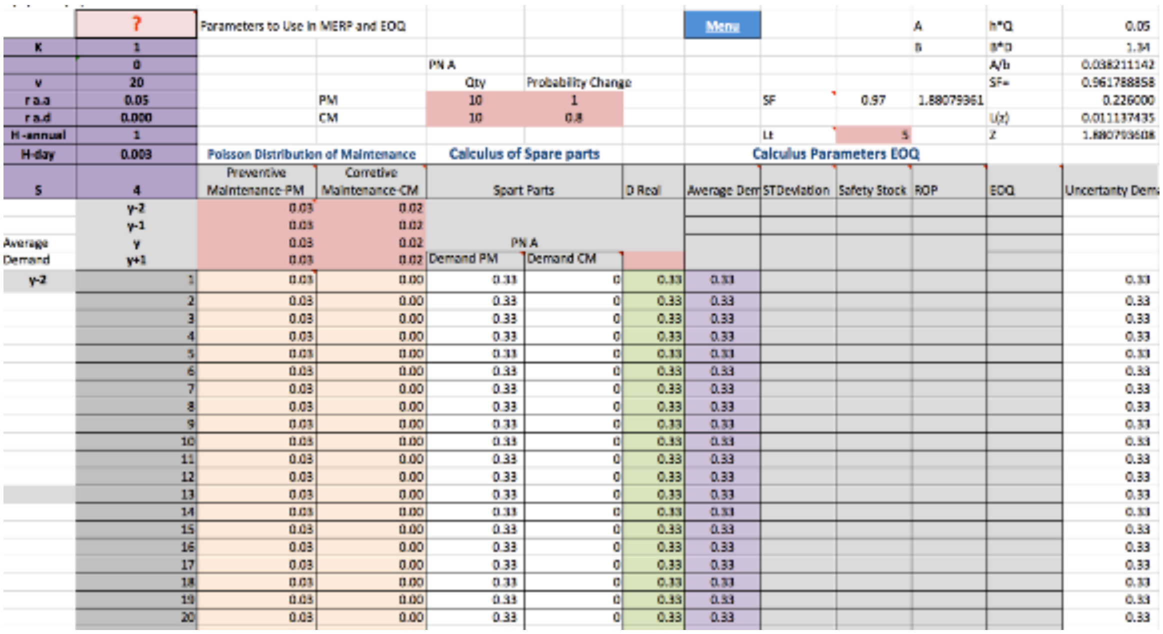
Table 45. Parameter data from Experiment 2.

Parameters Table

	K	H	S	# Usage	Lt	MTBF
	100%	30%	100%	225	30	25%
	15%	22%	50%	125	15	100%
	5%	5%	20%	5	5	200%
1	1.00	0.30	1.00	225.00	30.00	0.25
2	1.00	0.30	1.00	225.00	30.00	1.00
3	1.00	0.30	1.00	225.00	30.00	2.00
4	1.00	0.30	1.00	225.00	15.00	0.25
5	1.00	0.30	1.00	225.00	15.00	1.00
6	1.00	0.30	1.00	225.00	15.00	2.00
7	1.00	0.30	1.00	225.00	5.00	0.25
8	1.00	0.30	1.00	225.00	5.00	1.00
9	1.00	0.30	1.00	225.00	5.00	2.00
10	1.00	0.30	1.00	125.00	30.00	0.25
11	1.00	0.30	1.00	125.00	30.00	1.00
12	1.00	0.30	1.00	125.00	30.00	2.00
13	1.00	0.30	1.00	125.00	15.00	0.25
14	1.00	0.30	1.00	125.00	15.00	1.00
15	1.00	0.30	1.00	125.00	15.00	2.00
16	1.00	0.30	1.00	125.00	5.00	0.25
17	1.00	0.30	1.00	125.00	5.00	1.00
18	1.00	0.30	1.00	125.00	5.00	2.00
19	1.00	0.30	1.00	5.00	30.00	0.25
20	1.00	0.30	1.00	5.00	30.00	1.00
21	1.00	0.30	1.00	5.00	30.00	2.00
22	1.00	0.30	1.00	5.00	15.00	0.25
23	1.00	0.30	1.00	5.00	15.00	1.00
24	1.00	0.30	1.00	5.00	15.00	2.00
25	1.00	0.30	1.00	5.00	5.00	0.25
26	1.00	0.30	1.00	5.00	5.00	1.00
27	1.00	0.30	1.00	5.00	5.00	2.00
28	1.00	0.30	0.50	225.00	30.00	0.25
29	1.00	0.30	0.50	225.00	30.00	1.00
30	1.00	0.30	0.50	225.00	30.00	2.00
31	1.00	0.30	0.50	225.00	15.00	0.25
32	1.00	0.30	0.50	225.00	15.00	1.00
33	1.00	0.30	0.50	225.00	15.00	2.00
34	1.00	0.30	0.50	225.00	5.00	0.25
35	1.00	0.30	0.50	225.00	5.00	1.00
36	1.00	0.30	0.50	225.00	5.00	2.00

Table 46. Simulation consumption and EOQ/ROP calculation.

Simulation Consumption and EOQ/ROP Calculation

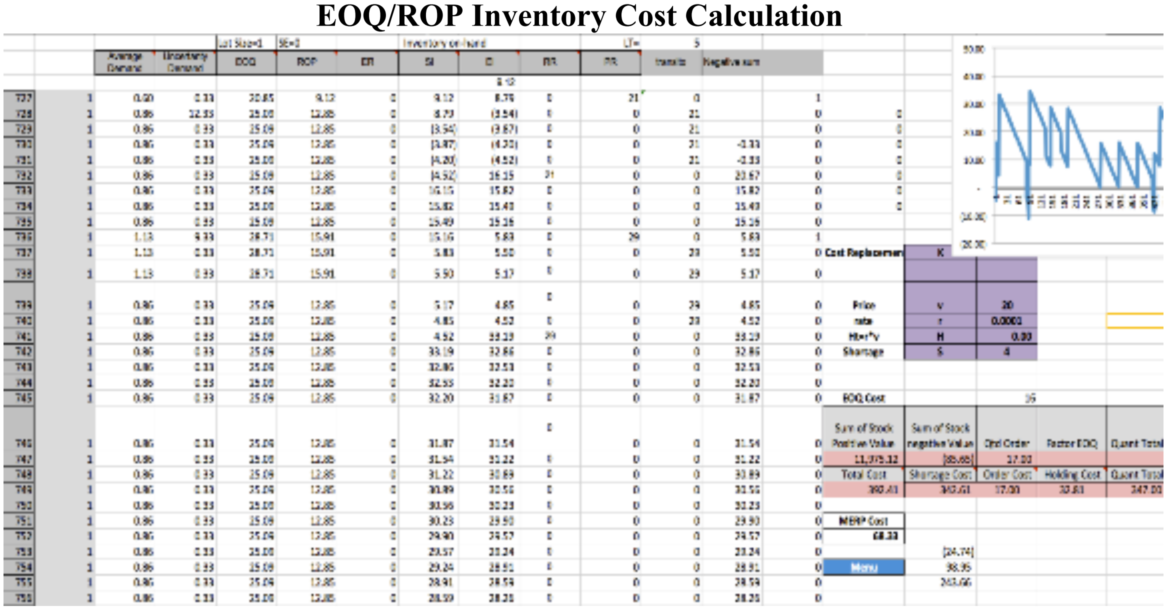


	?	Parameters to Use in MERP and EOQ				Menu			A	h*Q	0.05
K	1								B	B*D	1.34
	0		PN A							A/b	0.038211142
v	20		Qty	Probability Change						SF=	0.961788858
r a.a	0.05	PM	10	1			SF	0.97	1.88079361		0.226000
r a.d	0.000	CM	10	0.8						L(z)	0.011137435
H-annual	1						Lt	5		Z	1.880793608
H-day	0.003	Poisson Distribution of Maintenance		Calculus of Spare parts			Calculus Parameters EOQ				

	S 4	Preventive Maintenance-PM	Corretive Maintenance-CM	Sport Parts		D Real	Average Dem	STDeviation	Safety Stock	ROP	EOQ	Uncertanty Dem
	y-2	0.03	0.02									
	y-1	0.03	0.02									
Average	y	0.03	0.02	PN A								
Demand	y+1	0.03	0.02	Demand PM	Demand CM							
y-2	1	0.03	0.00	0.33	0	0.33	0.33					0.33
	2	0.03	0.00	0.33	0	0.33	0.33					0.33
	3	0.03	0.00	0.33	0	0.33	0.33					0.33
	4	0.03	0.00	0.33	0	0.33	0.33					0.33
	5	0.03	0.00	0.33	0	0.33	0.33					0.33
	6	0.03	0.00	0.33	0	0.33	0.33					0.33
	7	0.03	0.00	0.33	0	0.33	0.33					0.33
	8	0.03	0.00	0.33	0	0.33	0.33					0.33
	9	0.03	0.00	0.33	0	0.33	0.33					0.33
	10	0.03	0.00	0.33	0	0.33	0.33					0.33
	11	0.03	0.00	0.33	0	0.33	0.33					0.33
	12	0.03	0.00	0.33	0	0.33	0.33					0.33
	13	0.03	0.00	0.33	0	0.33	0.33					0.33
	14	0.03	0.00	0.33	0	0.33	0.33					0.33
	15	0.03	0.00	0.33	0	0.33	0.33					0.33
	16	0.03	0.00	0.33	0	0.33	0.33					0.33
	17	0.03	0.00	0.33	0	0.33	0.33					0.33
	18	0.03	0.00	0.33	0	0.33	0.33					0.33
	19	0.03	0.00	0.33	0	0.33	0.33					0.33
	20	0.03	0.00	0.33	0	0.33	0.33					0.33

Table 47. EOQ/ROP inventory costs calculation.

EOQ/ROP Inventory Cost Calculation



		Average Demand	Uncertanty Demand	EOQ (Lot Size=1)	ROP (SE=0)	ER	SI (Inventory on-hand)	EI	RR	PR (LT=)	transits (5)	Negative sum		
								8.12						
727	1	0.80	0.33	20.85	9.12	0	9.12	8.79	0	21	0		1	
728	1	0.86	12.33	25.08	12.85	0	8.79	(3.54)	0	0	21		0	0
729	1	0.86	0.33	25.09	12.85	0	(3.54)	(3.87)	0	0	21		0	0
730	1	0.86	0.33	25.09	12.85	0	(3.87)	(4.20)	0	0	21	-0.33	0	0
731	1	0.86	0.33	25.08	12.85	0	(4.20)	(4.52)	0	0	21	-0.33	0	0
732	1	0.86	0.33	25.09	12.85	0	(4.52)	16.15	21	0	0	20.67	0	0
733	1	0.86	0.33	25.09	12.85	0	16.15	15.82	0	0	0	15.82	0	0
734	1	0.86	0.33	25.08	12.85	0	15.82	15.49	0	0	0	15.49	0	0
735	1	0.86	0.33	25.09	12.85	0	15.49	15.16	0	0	0	15.16	0	
736	1	1.13	9.33	28.71	15.91	0	15.16	5.83	0	29	0	5.83	1	
737	1	1.13	0.33	28.71	15.91	0	5.83	5.50	0	0	29	5.50	0	
738	1	1.13	0.33	28.71	15.91	0	5.50	5.17	0	0	29	5.17	0	
739	1	0.86	0.33	25.09	12.85	0	5.17	4.85	0	0	29	4.85	0	
740	1	0.86	0.33	25.08	12.85	0	4.85	4.52	0	0	29	4.52	0	
741	1	0.86	0.33	25.08	12.85	0	4.52	33.19	29	0	0	33.19	0	
742	1	0.86	0.33	25.09	12.85	0	33.19	32.86	0	0	0	32.86	0	
743	1	0.86	0.33	25.09	12.85	0	32.86	32.53	0	0	0	32.53	0	
744	1	0.86	0.33	25.08	12.85	0	32.53	32.20	0	0	0	32.20	0	
745	1	0.86	0.33	25.09	12.85	0	32.20	31.87	0	0	0	31.87	0	
746	1	0.86	0.33	25.09	12.85	0	31.87	31.54	0	0	0	31.54	0	
747	1	0.86	0.33	25.08	12.85	0	31.54	31.22	0	0	0	31.22	0	
748	1	0.86	0.33	25.09	12.85	0	31.22	30.89	0	0	0	30.89	0	
749	1	0.86	0.33	25.09	12.85	0	30.89	30.56	0	0	0	30.56	0	
750	1	0.86	0.33	25.08	12.85	0	30.56	30.23	0	0	0	30.23	0	
751	1	0.86	0.33	25.09	12.85	0	30.23	29.90	0	0	0	29.90	0	
752	1	0.86	0.33	25.09	12.85	0	29.90	29.57	0	0	0	29.57	0	
753	1	0.86	0.33	25.08	12.85	0	29.57	29.24	0	0	0	29.24	0	
754	1	0.86	0.33	25.09	12.85	0	29.24	28.91	0	0	0	28.91	0	
755	1	0.86	0.33	25.09	12.85	0	28.91	28.59	0	0	0	28.59	0	
756	1	0.86	0.33	25.08	12.85	0	28.59	28.26	0	0	0	28.26	0	

Cost Replacemen	K			
Price	v	20		
rate	r	0.0001		
Hb=r*v	H	0.00		
Shortage	S	4		
EOQ Cost		16		
Sum of Stock Positive Value	Sum of Stock negative Value	Qtd Order	Factor EOQ	Quant Total
11,975.12	(85.65)	17.00		
Total Cost	Shortage Cost	Order Cost	Holding Cost	Quant Total
392.41	342.61	17.00	32.81	347.00
MERP Cost				
68.33				
	(24.74)			
Menu	98.95			
	243.66			

Table 48. MERP inventory costs calculation.

MERP Inventory Cost Calculation

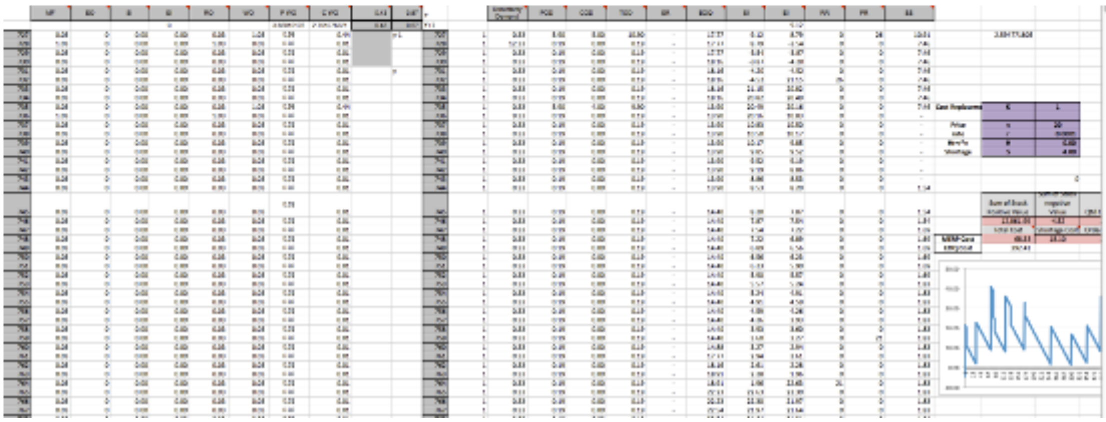


Table 49. Inventory costs results.

Result a sample record

	K	H	$	# Usage	LT (dias)	MTBUR (≈TBO)	Total Cost	Shortage Cost	Order Cost	Holding Cost	Quant Total	Average Stock	Qtd of shortage	Qtd Order		Total Cost	Shortage Cost	Order Cost	Holding Cost	Quant Total	Average Stock	Qtd of shortage	Qtd Order
2	1.00	0.00	4.00	5.00	5.00	6,000.00	68.33	18.10	15.00	35.24	378.00	123.67	4.52	15.00	EOQ/ROP	392.41	342.61	17.00	32.81	347.00	16.40	85.65	17.00
3																							
4																							

Table 50. Sample result of a situation.

Sample Result

1	49,446.28	2,240.00	4,791.15	45,114.00	399.26	2,472.31	112.00
2	43,346.80	2,280.00	4,807.89	46,910.00	400.66	2,167.34	114.00
3	7,275.52	2,280.00	5,146.84	46,565.00	428.90	363.78	114.00
4	6,924.94	2,260.00	4,677.79	46,238.00	389.82	346.25	113.00
5	30,004.86	2,280.00	4,675.77	46,201.00	389.65	1,500.24	114.00
6	11,054.31	2,260.00	5,095.19	46,081.00	424.60	552.72	113.00
7	23,280.85	2,280.00	4,982.45	47,084.00	415.20	1,164.04	114.00
8	68,135.08	2,300.00	4,967.14	46,950.00	413.93	3,406.75	115.00
9	14,702.27	2,260.00	5,002.74	45,880.00	416.90	735.11	113.00
10	10,971.67	2,300.00	4,813.36	47,612.00	401.11	548.58	115.00
11	13,441.63	2,320.00	4,654.40	47,656.00	387.87	672.08	116.00
12	23,269.57	2,280.00	4,812.92	46,504.00	401.08	1,163.48	114.00
13	15,091.45	2,260.00	5,113.52	46,132.00	426.13	754.57	113.00
14	44,681.11	2,260.00	5,137.93	45,617.00	428.16	2,234.06	113.00
15	40,726.63	2,280.00	4,585.82	46,985.00	382.15	2,036.33	114.00
16	7,684.13	2,280.00	4,625.16	46,460.00	385.43	384.21	114.00
17	20,642.79	2,240.00	5,052.31	45,520.00	421.03	1,032.14	112.00
18	37,876.38	2,300.00	4,823.37	46,989.00	401.95	1,893.82	115.00
19	6,786.27	2,280.00	5,032.25	46,216.00	419.35	339.31	114.00
20	20,113.32	2,300.00	5,142.48	47,638.00	428.54	1,005.67	115.00
21	44,440.89	2,280.00	5,010.97	46,161.00	417.58	2,222.04	114.00
22	33,064.16	2,280.00	4,920.55	46,701.00	410.05	1,653.21	114.00
23	20,619.58	2,280.00	4,866.22	45,885.00	405.52	1,030.98	114.00
24	43,977.14	2,280.00	4,712.76	47,063.00	392.73	2,198.86	114.00
25	25,987.01	2,280.00	4,855.10	46,627.00	404.59	1,299.35	114.00
26	26,341.29	2,300.00	5,006.81	47,164.00	417.23	1,317.06	115.00
27	38,955.88	2,280.00	5,115.04	46,175.00	426.25	1,947.79	114.00
28	24,608.17	2,260.00	4,935.67	45,886.00	411.31	1,230.41	113.00
29	14,114.90	2,280.00	4,891.47	46,070.00	407.62	705.75	114.00
30	71,327.62	2,280.00	4,920.46	46,686.00	410.04	3,566.38	114.00
31	33,558.18	2,280.00	5,087.63	46,621.00	423.97	1,677.91	114.00
32	27,082.30	2,260.00	4,914.39	46,004.00	409.53	1,354.11	113.00
33	6,672.49	2,260.00	5,134.85	46,142.00	427.90	333.62	113.00
34	22,713.72	2,300.00	4,814.62	46,681.00	401.22	1,135.69	115.00
35	28,797.86	2,300.00	4,639.51	46,953.00	386.63	1,439.89	115.00
36	15,375.93	2,240.00	4,936.71	44,848.00	411.39	768.80	112.00
37	32,991.50	2,260.00	5,037.80	46,180.00	419.82	1,649.57	113.00
38	30,736.73	2,300.00	4,711.38	46,568.00	392.61	1,536.84	115.00
39	10,211.89	2,260.00	4,974.81	46,472.00	414.57	510.59	113.00
40	14,468.51	2,240.00	5,231.52	45,789.00	435.96	723.43	112.00
41	16,152.61	2,280.00	5,014.71	46,373.00	417.89	807.63	114.00
42	83,240.89	2,280.00	4,968.56	46,611.00	414.05	4,162.04	114.00
43	19,559.73	2,280.00	4,979.98	46,062.00	415.00	977.99	114.00
44	47,895.55	2,240.00	5,055.80	45,377.00	421.32	2,394.78	112.00
45	11,508.15	2,240.00	5,057.16	45,574.00	421.43	575.41	112.00
46	20,053.94	2,300.00	4,708.80	47,140.00	392.40	1,002.70	115.00
47	21,687.83	2,280.00	4,769.98	46,524.00	397.50	1,084.39	114.00
48	74,308.45	2,260.00	4,860.34	46,188.00	405.03	3,715.42	113.00
49	39,679.73	2,280.00	5,180.80	45,713.00	431.73	1,983.99	114.00
50	39,991.15	2,300.00	4,663.96	46,490.00	388.66	1,999.56	115.00

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